COMPUTATIONAL MODELING OF DYNAMIC
FAILURE MECHANISMS IN
ARMOR/ANTI-ARMOR MATERIALS

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Final Report

S.P. Andrew, R.D. Caligiuri, T.K. Parnell, and L.E. Eiselstein

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Stephen P. Andrew, Robert D. Caligiuri, T.K. Parnell, and Lawrence E. Eiselstein

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Failure Analysis Associates, Inc.
149 Commonwealth Drive
Menlo Park, CA 94025

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13. ABSTRACT (Maximum 200 words)

The purpose of this project was to develop improved dynamic failure models for brittle materials (primarily ceramics). The approach to developing these failure models was to establish a database (ACERAM) in which fundamental material properties and processing information could be directly correlated with ballistic performance data. Under this contract, a comprehensive literature search was conducted, many contacts were established in the armor/anti-armor research and development community, and database development was undertaken. A more limited project was also undertaken to assess and compare the effects of material properties and penetration mechanisms on the ballistic performance of depleted uranium and tungsten alloy penetrators.

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CONTENTS

1.0 INTRODUCTION

Failure Analysis Associates, Inc. (FaAA) was funded under the Computational Mechanics Program element of the Balanced Technology Initiative (BTI) to develop improved dynamic failure models for brittle materials (primarily ceramics). Our approach to developing these failure models was to establish a database (ACERAM) in which fundamental material properties and processing information could be directly correlated with ballistic performance data.

1.1 Background

The data collection and database development step was nearly completed under BTI funding, which covered the contract from October 1988 to September 1990. The project was then extended (without funds) to September 1991 and funding was sought to (1) expand data collection activities to complete the database and (2) apply FaAA-developed statistical analysis techniques to critically evaluate the data and to identify those fundamental physical and microstructural properties that control the deformation (if any) and failure of brittle materials during penetration. This planned approach is shown schematically in Figure 1. In fact, however, FaAA's proposal for additional funding was rejected in December 1991. This final report, therefore, documents the contract effort to September 1990 and subsequent publications stemming from this work.

1.2 Problem Statement

The select database of "useful" information on the ballistic performance of ceramics that was to result from this project would have been the most extensive ever constructed in the free world. Existing ballistic data bases (there are at least two other available ceramic armor data bases, AADS [1] and Chicken Little [2]) contain little specific information on materials properties and characteristics, nor are they necessarily structured to permit one-to-one comparisons of the effect of specific materials characteristics on performance under equivalent ballistic test conditions. Because of its size and scope, the comprehensive materials-oriented database for brittle armor materials that was to result from this project would have enabled researchers to determine key properties and processing variables on which to focus their efforts.
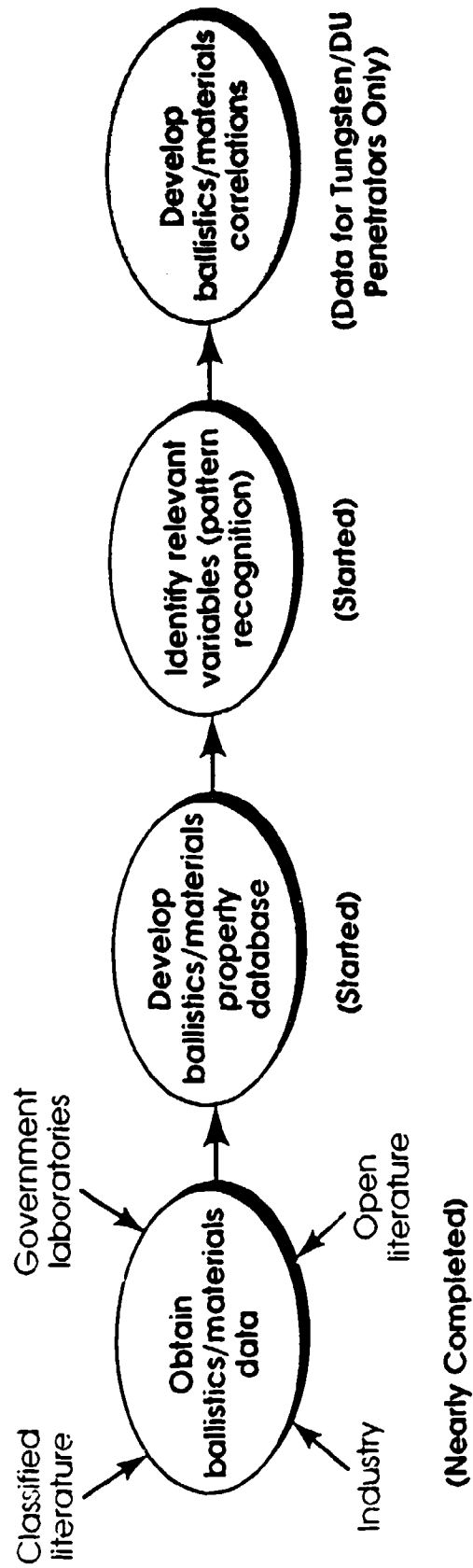
1

Figure 1: Project Flowchart, Showing Levels of Completion at Project Close

2.0 SUMMARY OF RESULTS

The emphasis of the project in the first two years was to evaluate the literature and survey private industry and government laboratories for appropriate data. Several hundred open literature papers and technical reports were reviewed for usable data, and links were established with available existing databases. A committee -- consisting of representatives from FaAA, the U.S. Army Tank Command (TACOM), the Army Materials Technology Laboratory (AMTL), the Ballistics Research Laboratory (BRL), and Los Alamos National Laboratory (LANL) -- was also formed early in the project to oversee our data collection activities (to prevent duplication) and to develop a standardized list of properties and processing variables to be collected on candidate brittle armor materials.

2.1 Data Collection

Data (both classified and unclassified) was collected from existing databases, from published reports/papers in the open literature, and from unpublished test data from government, university, and industry laboratories on the subjects of (1) ballistic performance of ceramics and (2) ceramic material properties governing impact performance. As a result of these efforts, an extensive collection of useful data was compiled for initial analyses of the material and processing variables that affect the ballistic performance of ceramics. Unclassified reports/papers containing material that contributed significantly to the database include those from Lawrence Livermore National Laboratory (LLNL), the Naval Research Laboratory (NRL), the University of California at Berkeley (UCB), and AMTL, among others. Those unclassified papers that were determined to be most useful are listed in Table 1.

Classified papers that we expected to be useful in this research are identified in Table 2. Appropriate clearance was established with DTIC late in the project, so collection and review of this material never began.

FaAA was also able to establish some important industry and government contacts who agreed to contribute data to this program. A listing of the data that has been

Table 1
USEFUL DATA SOURCES FROM THE OPEN LITERATURE

Ferguson, W.J. and Rice, W.J. "Effect of Microstructure on the Ballistic Performance of Alumina," Naval Research Laboratory, NRL Memorandum Report 2302, August 1971.

Landingham, R.L. and A.W. Casey, *Semiannual Progress Report of the Light-Armor Materials Program*, Lawrence Radiation Laboratory, University of California, Livermore, UCRL-51066, June 1971.

Mayseless, M., Goldsmith, W., Virostek, S.P., and Finnegan, S.A., "Impact on Ceramic Targets," *Impact Loading and Dynamic Behaviour of Materials*, editor: Chien, C.Y., Oberursel, Germany: DGM Informationalsgesellschaft mit beschrankter Haftung, Vol 1, 1988, pp. 407-414.

Mescall, J.F. and Tracy, C., "Improved Modeling of Fracture in Ceramic Armors," *Army Science Conference Proceedings*, Vol 3, June 17-19, 1986, pp. 41-53.

Rosenberg, Z. and Yeshurun, Y., "The Relationship Between Ballistic Efficiency and Compressive Strength of Ceramic Tiles," *International Journal of Impact Engineering*, Vol. 7, no. 3, 1988, pp. 357-362.

Rosenberg, Z., Bless, S.J., Yeshrun, Y., and Okajima, K., "A New Definition of Ballistic Efficiency of Brittle Materials Based on the Use of Thick Backing Plates," *Impact Loading and Dynamic Behaviour of Materials*, editor: Chiem, C.Y, et al., Oberursel, Germany: DGM Informationalsgesellschaft mit beschrankter Haftung, 1988, pp. 491-498.

Tracy, C., Slavin, M., and Viechnicki, D., "Ceramic Fracture During Ballistic Impact," *Fractography of Glasses and Ceramics (Advances in Ceramics)*, American Ceramic Society, Westerville, Ohio, Vol 22, 1988, pp. 295-306.

Table 1 Continued

Viechinicki, D., Blumenthal, W., Slavin, M., Tracy, C., and Skeele, H., "Armor Ceramics-1987," *Third TACOM Armor Coordinating Conference for Light Combat Vehicles*, Vol. 1, February 17-19, 1987, Monterey, California.

Viechnicki, D.J., "Factors Controlling the Ballistic Behavior of Armor Ceramics," *Army Science Conference Proceedings*, Vol 4, June 17-19, 1986, pp. 233-247.

Wilkins, M.L., "Use of Boron Carbides in Lightweight Armor," *Boron and Refractory Borides*, editor: Matkovitch, V.I., Springer-Verlag, Berlin, Germany, 1977, pp. 633-648.

Wilkins, M.L., C.R. Cline, and C.A. Honodel, *Fourth Progress Report of Light Armor Program*, Lawrence Radiation Laboratory, University of California, Livermore, UCRL-50694, 1969.

Wilkins, M.L., R.L. Landingham, and C.A. Honodel, *Fifth Progress Report of Light Armor Program*, Lawrence Radiation Laboratory, University of California, Livermore, UCRL-50980, January 1971.

Wilkins, M.L., *Third Progress Report of Light Armor Program, Lawrence Radiation Laboratory*, University of California, Livermore, UCRL-50460, 1968.

Xavier, C. and da Costa, C.R.C., "A Study of the Mechanical Behavior in Ballistic Impact of Alumina Plates," *Ceramica*, Vol 30, No. 175, July 1984.

Table 2
USEFUL CLASSIFIED LITERATURE DATA SOURCES

Abbott, K.H. and Semple, C.W., "Attributes and Limitations of Lightweight Armor," *Proceedings of Symposium on Lightweight Armor Materials*, AMRA MS-65-01, 326-339, AD 360 764L, U.S. Army Materials Research Agency, March 1965. (Secret Report).

Adams, Hale, and Zwissler, "Advanced Materials Technology Development Project Phase 1," JPL Report No. D-382, Vol. IV, Part 1, January 1, 1983.

Amos, C.W., "Dissemination of Armor Materials Ballistic Performance," *Proceedings of Symposium on Lightweight Armor Materials*, AMRA MS-65-01, AD 360 764L, March 1965, pp. 295-301, (Secret Report).

Askins, D., Bless, S., Hanchak, S., Hartman, D , and Ror.leau, R., "Multi-hit Ceramic Armor for 30APM2," *Fourth TACOM Armor Coordinating Conference*, Vol 2, 1988.

Contiliano and Thorpe, "ARAP Activity During Phase 2 of Lightweight Structural Armor Program," ARAP Report #510, December 1, 1983.

Contiliano, R.M. "1982 Annual — DARPA Composite Armor Technology Program," ARAP Report #497, AD-C034-846, May 1, 1983.

Contiliano and Snedeker, "In proved Lightweight Structural Armor," ARAP Report NSWC TR82-48, August 1, 1981.

Contiliano and Snedeker, "Annual Report for 1981 in Composite Armor Technology Program," ARAP Report No. 455, Vol. 2, December 1, 1981.

Table 2 Continued

Florence, A.L. and Ahrens, T.J., "Interaction of Projectiles and Composite Armor," AMRA CR. 67-05 (F), U.S. Army Materials Research Agency, Watertown, Massachusetts, January 1967.

Gooch, W. "30-mm APDS Threat Surrogate," BRL-MR-3568, March 1, 1987.

Mascianica, F.S., "Ballistic Technology of Lightweight Armor," AMMRC TR 81-20, May 1, 1981.

Mascianica, F.S., "Effect of Back-up Thickness of 2024 Aluminum on the Ballistic Efficiency of Al_2O_3 Aluminum Composites," AMRA TA AB1-10, U.S. Army Materials Research Agency, June 1965 (Confidential Report).

Mascianica, F.S., "Effect of Boron Carbide Tile Size on Ballistic Efficiency," AMRA TR AB1-5, U.S. Army Materials Research Agency, April 1965 (Secret Report).

Persh, J., "DOD Armor Materials Programs," DCIC Current Awareness Bulletin, Office of the Director of Defense Research and Engineering, Chemical Technology, Materials Division, No. 14, 12-13, January - February 1969.

Reed, E.L., and Kruegel, S.L., "Correlation of Microstructure and Ballistic Properties of Armor Plate," Report 710/261, AD 626 124, U.S. Army Watertown Arsenal, July 11, 1938.

Semple, C.W., "Ballistic Behavior of Ceramic Composite Armors," AD 374 334, U.S. Army Materials Research Agency, June 1966 (Secret report).

Semple, C.W., "Ceramic Composite Armors,"AMRA TR -65-26, AD 367 071L, U.S. Army Materials Research Agency, October 1965 (Secret Report).

Table 2 Continued

Semple, C.W., "Fundamental Material Properties Effects on Ballistic Protection of Lightweight Ceramic Composite Armor," AMRA TR-65-06, AD 362 260L, U.S. Army Research Agency, April 1965 (Secret Report).

U.S. Army Tank Automotive Command, *Second TACOM Armor Coordinating Conference for Light Combat Vehicles*, November 1, 1985.

Tarpinian, A., Semple, C.W., and Hannon, F.S., "Ceramic Armor," *Proceedings of the Second Symposium on Lightweight Armor Materials*, AMRA MS-66-07, AD 378 972, U.S. Army Materials Research Agency, Vol.1, October 1966, pp. 215-254 (Secret Report).

Taylor, J.W., "Properties of Materials of Interest for Lightweight Armor," Report LA-3858-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, January 22, 1968 (Confidential).

Wilkins, Herd, and Snowden, "Advanced Armor System to Defeat KE Projectiles and Precision Shaped Charges," UCAL-53268-82, Lawrence Livermore Laboratories, May 1, 1982.

"Representation and Use of Ballistic Limit Data," AB1-65, U.S. Army Materials and Mechanics Research Center, Prototypes Laboratory, January 15, 1967 (Special).

contributed to the analysis effort is presented in Appendix A. Programs and organizations that had promised additional information include:

- **Dow Chemical** — Dow has collected much data on the ballistic performance of ceramic armors over the last few years. They agreed to send us the aluminum nitride data that they have collected as part of the BTI program.

- **W.R. Grace** —W.R. Grace agreed to send us ballistic test data on Al_2O_3, TiB_2, SiC, and A•B (Al_2O_3 and B_4C) samples that they have formulated.

- **DARPA Armor program** — Ballistic test data from the participants in the Blue Armor Program [DUPONT, ALCOA, Alliant Tech Systems (formerly Honeywell), and FMC] would have been an important addition to the database.

- **University of Dayton Research Institute (UDRI)** — UDRI agreed to send us draft copies of classified work that they are doing with lightweight ceramic armors for Wright-Patterson Air Force Base.

- **Coors Ceramics Company** — Coors agreed to work with us in identifying material properties and processing techniques for any materials manufactured by Coors that are not reported in available research papers or reports.

The following government laboratories also provided previously unpublished data to the project:

- **Los Alamos National Laboratory** — LANL was completing a test program on the ballistic performance of B_4C and Al_2O_3 ceramics. They agreed to send a copy of the unclassified preliminary report, and a copy of the final report when it becomes available. We were sent a copy of the Phermex photographs of this test program.

  LANL was also monitoring a test program to evaluate the ballistic performance of B_4C and SiC ceramics.

- **Ballistics Research Laboratory** — BRL has a significant amount of ballistics data on SiC, B_4C, and Al_2O_3 that had not yet been published.

If a follow-on study is ever funded, it would be worthwhile to pursue these contacts.

2.2 Database Development

The format for the database was established and is shown in Figure 2. The completed database, called ACERAM (Advanced CERamic ArMor), would have used the "4th dimension" relational database software on a Macintosh computer. It was anticipated that this user-friendly database would be the most complete set of "useful" data on the ballistic performance of ceramics that had ever been assembled, and that its data set would be the foundation for the data correlation analysis effort. This is as far as the database development effort progressed under the aborted contract.
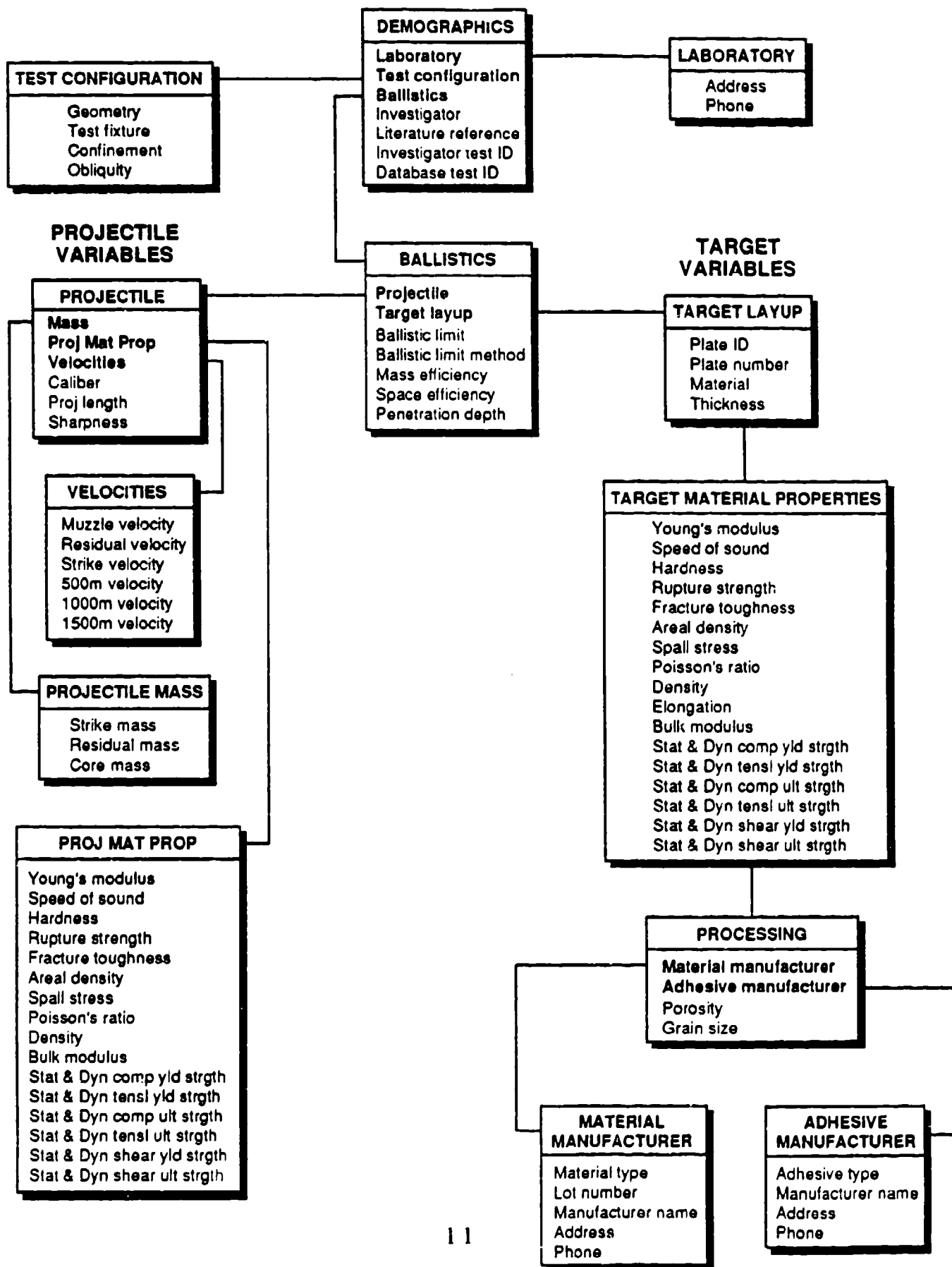
2.3 Tungsten/Depleted Uranium Review

In a related effort, FaAA was asked to review the information available on the dynamic properties of tungsten and DU, and review the mechanisms of penetration and ballistic performance for these two materials. This review, "A Review of High Strain Rate Properties and Penetration Mechanisms of Depleted Uranium and Tungsten Alloys," was presented at the April 1990 ARDEC/ARO workshop on "Metallurgical Aspects of Deformation/Failure Mechanisms in (The Terminal Ballistics of Heavy Metal) Kinetic Energy Penetrator Materials." The purpose of the workshop was to evaluate the current status of properties, penetration mechanisms, and performance of tungsten and DU penetrators. Penetration mechanisms are of particular interest, as it is felt that the differences in these mechanisms may be the reason why DU and tungsten penetrators perform differently.

In support of this effort, FaAA reviewed classified and unclassified literature and contacted government agencies, federal and university laboratories, and private industries. These efforts provided us with over 100 papers/reports on tungsten/DU penetration and over 30 government and industry contracts.

A detailed review paper was submitted to The Minerals, Metals, and Materials Society (TMS) and published by them in 1991. A copy of this paper is included as Appendix B.

Figure 2 Army CERamic ArMor Database Layout

DEMOGRAPHICS
- Laboratory
- Test configuration
- Ballistics
- Investigator
- Literature reference
- Investigator test ID
- Database test ID

LABORATORY
- Address
- Phone

TEST CONFIGURATION
- Geometry
- Test fixture
- Confinement
- Obliquity

PROJECTILE VARIABLES

PROJECTILE
- Mass
- Proj Mat Prop
- Velocities
- Caliber
- Proj length
- Sharpness

BALLISTICS
- Projectile
- Target layup
- Ballistic limit
- Ballistic limit method
- Mass efficiency
- Space efficiency
- Penetration depth

TARGET VARIABLES

TARGET LAYUP
- Plate ID
- Plate number
- Material
- Thickness

VELOCITIES
- Muzzle velocity
- Residual velocity
- Strike velocity
- 500m velocity
- 1000m velocity
- 1500m velocity

TARGET MATERIAL PROPERTIES
- Young's modulus
- Speed of sound
- Hardness
- Rupture strength
- Fracture toughness
- Areal density
- Spall stress
- Poisson's ratio
- Density
- Elongation
- Bulk modulus
- Stat & Dyn comp yld strgth
- Stat & Dyn tensl yld strgth
- Stat & Dyn comp ult strgth
- Stat & Dyn tensl ult strgth
- Stat & Dyn shear yld strgth
- Stat & Dyn shear ult strgth

PROJECTILE MASS
- Strike mass
- Residual mass
- Core mass

PROJ MAT PROP
- Young's modulus
- Speed of sound
- Hardness
- Rupture strength
- Fracture toughness
- Areal density
- Spall stress
- Poisson's ratio
- Density
- Bulk modulus
- Stat & Dyn comp yld strgth
- Stat & Dyn tensl yld strgth
- Stat & Dyn comp ult strgth
- Stat & Dyn tensl ult strgth
- Stat & Dyn shear yld strgth
- Stat & Dyn shear ult strgth

PROCESSING
- Material manufacturer
- Adhesive manufacturer
- Porosity
- Grain size

MATERIAL MANUFACTURER
- Material type
- Lot number
- Manufacturer name
- Address
- Phone

ADHESIVE MANUFACTURER
- Adhesive type
- Manufacturer name
- Address
- Phone

FaAA's conclusions, based on available data, include:

- DU and tungsten alloys respond differently to high rate loading conditions, both in terms of mechanical properties and failure (penetration) mechanisms.
  - Under tensile loading, DU alloys exhibit a higher ultimate tensile strength and a higher strain to failure than do tungsten alloys.
  - Under shear loading, DU and tungsten alloys exhibit similar strengths, but DU exhibits a higher strain to failure.
  - Against steel targets, both DU and tungsten tips undergo ductile flow. However, subsequent penetration results in bulged tip sharpening by shearing (adiabatic or not). This sharpening ocurs more readily in DU than in tungsten.
  - Against ceramic composite targets, tungsten alloys penetrate by erosion/localized plastic deformation.

- The ballistic performance of DU and tungsten alloys against monolithic steel targets is similar -- at best a 5 to 10% difference. Current improvements in mechanical properties of DU and tungsten alloys give at best a 5 to 10% improvement in ballistic performance.

- Against oblique spaced arrays, DU alloys significantly outperform tungsten alloys. An increase in ductility/toughness in either alloy can result in a substantial improvement in ballistic performance.

- Based on our preliminary findings, it appears that the best way (in the short-term) to improve the ballistic performance of tungsten alloy penetrators against oblique spaced arrays is to improve their resistance to fracture during penetration.

- Based on our preliminary findings, it may also be ultimately possible to achieve a sharp tip during penetration in tungsten alloys by proper microstructural control.

3.0 OTHER CONTRACT REQUIREMENTS

The following sections present all contract-required information not covered by the summary of contract work.

3.1 List of all Publications and Technical Reports

- Andrew, S.P., R.D. Caligiuri, and L.E. Eiselstein, "Relationship between Dynamic Properties and Penetration Mechanisms of Tungsten and Depleted Uranium

Penetrators," Proceedings of the International Symposium on Ballistics, Stockholm, Sweden (to be presented/published June 1992).

- Andrew, S.P., R.D. Caligiuri, and L.E. Eiselstein, "A Review of Penetration Mechanisms and Dynamic Properties of Tungsten and Depleted Uranium Penetrators," *Tungsten and Tungsten Alloys – Recent Advances*, ed. Andrew Crowson and Edward S. Chen, The Minerals, Metals, & Materials Society, 1991, pp. 141-149.

- Caligiuri, R.D., S.P. Andrew, and T.K. Parnell, "Computational Modeling of Dynamic Failure in Armor/Anti-Armor Materials," Quarterly and Semi-Annual Progress Reports for Contract DAAL03-88-C-0029, Army Research Office Proposal number 26164-MS-A (period covered: October 1988 to September 1991).

3.2 List of All Participating Technical Personnel

Dr. Robert D. Caligiuri
Dr. Lawrence E. Eiselstein
Mr. Stephen P. Andrew
Dr. T. Kim Parnell

No advanced degrees were earned by these participants during the contract effort.

3.3 Report of Inventions

No inventions resulted from this contract effort

3.4 Bibliography

Bibliographic compilations are presented in Appendix A, which is a listing of data sources compiled for this contract, and Appendix B, which contains an extensive tungsten/DU reference listing compiled under this contract. In the interest of brevity, these will not be repeated here.

4.0 REFERENCES

1. Miller, R.T., "The TACOM/DARPA Automated Armor Database System," *Third TACOM Armor Coordinating Conference for Light Combat Vehicles*, Vol. I, 1987.

2. Szabo, S. and Dyess, W.W., "The New National Armor-Anti Armor Data Repository," *Fourth TACOM Coordinating Conference*, Vol. 2, 1988.

APPENDIX A
LISTING OF SOURCES FOR CERAMIC DATABASE

Army Science 1986 Conference: Volume 3 Principal Authors M Through R.
Army Science 1986 Conference. West Point, NY. June 17-19, 1986.
Washington, DC: Department of the Army, 1986.

Ballistic Coefficients.
In: Sierra Bullets, n.d.: 359-417.

Ballistic Tests of Armor Materials: Final Report.
Aberdeen Proving Ground, MD: Army Test and Evaluation Command, April
6, 1977.

Ballistics 11th International Symposium: Volume 1 Propulsion Dynamics,
Launch Dynamics, Flight Dynamics.
Ballistics 11th International Symposium. Brussels, Belgium. May 9-11,
1989. n.s.: Belgian Royal Military Academy, 1989: v1.

Ballistics 11th International Symposium: Volume 2 Warhead Mechanisms,
Terminal Ballistics.
Ballistics 11th International Symposium. Brussels, Belgium. May 9-11,
1989. n.s.: Belgian Royal Military Academy, 1989: v2.

Ballistics 11th International Symposium: Volume 3 Body Armour and
Wound Ballistics, Weapon Identification.
Ballistics 11th International Symposium. Brussels, Belgium. May 9-11,
1989. n.s.: Belgian Royal Military Academy, 1989: v3.

Ballistics 7th International Symposium.
Ballistics 7th International Symposium. The Hague, Netherlands. April
19-21, 1983. The Hague, Netherlands: Seventh International Symposium on
Ballistics, 1983.

Ballistics 8th International Symposium.
Ballistics 8th International Symposium. Orlando, FL. October 23-25,
1984. Wilmington, MA: Avco Systems Division, 1984.

Ballistics 9th International Symposium: Volume 2.
Ballistics 9th International Symposium. Shrivenham, UK. April 29- May
1, 1986. n.s., 1986: v2.

DoD/DARPA Coordination Meeting on Advanced Armor/Anti-Armor Materials
and Advanced Computational Methods.
DoD/DARPA Coordination Meeting on Advanced Armor/Anti-Armor Materials
and Advanced Computational Methods. Alexandria, VA. December 13-15, 1988.
Alexandria, VA: Institute for Defense Analyses, March 1989: 2 volumes.

Fiberglass Armor Protects Carrier.
Machine Design, v59 n13, June 11, 1987: 16.

High Density Alloy Penetrator Materials 1977 Conference.
Watertown, MA: Army Materials and Mechanics Research Center, April
1977.

International Conference on Mechanical and Physical Behaviour of
Materials Under Dynamic Loading (Table of Contents only).
Journal de Physique, v49, September 1988: 11-17.

Kerals and Sitalls: An Assessment of Soviet Technology, Part 2.
McLean, VA: Technical Research Corp., September 21, 1987.

Lightweight Armor Protects Crucial Aircraft Parts.
Design News, v45 n2, January 23, 1989: 36.

Physical Properties of Tungsten-Nickel-Iron Alloys.
n.s., n.d.

Processing of Ceramics: An Assessment of Soviet Technology, Part 4.
McLean, VA: Technical Research Corp., June 1, 1988.

Review of Powder Metallurgy in the USSR: Working-Paper Report.
Columbus, OH: Battelle Columbus Laboratories, April 27, 1984.

S and T Terminology for Kinetic Energy Penetrators.
Columbus, OH: Battelle Columbus Division, October 7, 1988.

The Shock and Vibration Bulletin: Part 5 Shock, Fragility.
Washington, DC: Shock and Vibration Information Center, December
1970.

Third Progress Report of Light Armor Program.
n.s., n.d.

Tungsten Alloy Boosts Armour Penetration.
International Defense Review, v21 n9, 1988: 1217.

Tungsten and Tungsten Alloys: An Assessment of Soviet Technology, Part
6.
McLean, VA: Technical Research Corp., March 1, 1989.

US Army Test and Evaluation Command Test Operations Procedure--
Ballistic Tests of Armor Materials: Final Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory,
April 1977.

V50 Ballistic Test for Armor: Document Summary.
n.s., January 22, 1987.

Abey, A.E.; Stromberg, H.D.
Shear Strength of Beryllium, Uranium, and Tungsten as a Function of
Strain, Strain Rate, and Pressure.
Journal of Basic Engineering, v93D n2, June 1971: 291-295.

Abkowitz, Susan M.; Weihrauch, Paul; Abkowitz, Stanley; Mariano,
Stephen A.; Papetti, Dino.
Ductile Alloy Encapsulated Ceramic Armor Development: Final Report.
Watertown, MA: Army Materials Technology Laboratory, January 1990.

Ad Hoc Committee on Personnel Armor Materials.
The Development of Lightweight Armor.
n.s., June 1968.

Adams, Marc; Sines, George.
A Statistical, Micromechanical Theory of the Compressive Strength of
Brittle Materials.
Journal of the American Ceramic Society, v61 n3/4, March/April 1978:
126-131.

Ahrens, Thomas J.; Gust, W.H.; Royce, E.B.
Material Strength Effect in the Shock Compression of Alumina.
Journal of Applied Physics, v39 n10, September 1968: 4610-4616.

Aksay, I.A.; Kim, G.H.; Milius, D.L.; Sarikaya, M.; Stangle, G.C.;
Yasrebi, M.
High Performance Ceramic/Metal Composites.
Seattle, WA: University of Washington, n.d.

Alpa, G.
On a Statistical Approach to Brittle Rupture for Multiaxial States of
Stress.
Engineering Fracture Mechanics, v19 n5, 1984: 881-901.

Amelsfort, R.V.
Long Rod Penetration into a Semi-Infinite Target: Computer Code
Calculations Compared With Experimental Results.
The Hague, Netherlands: Prins Maurits Laboratorium, September 1930.

Amin, Kamal E.; Hartline, Stephen D.
Advanced Ceramics: A Challenge to Produce Reliable Components with
Known Properties.
ASTM Standardization News, v15 n10, October 1987: 50-55.

Anderson, Richard M.
Testing Advanced Ceramics.
Advanced Materials & Processes, v135 n3, March 1989: 31-36.

Aoki, S.; Ohta, I.; Sakata, M.; Ohnabe, H.
Time-Dependent Probability of Fracture and Distribution of Fracture
Location for Brittle Structures.
In: Structural Safety and Reliability 4th International Conference.
1985. n.s.: ICOSSAR, 1985: 2.451-2.460.

Armstrong, P.E.; Follansbee, P.S.; Zocco, T.
A Constitutive Description of the Deformation of Alpha Uranium Based
on the Use of the Mechanical Threshold Stress as a State Variable.
Los Alamos, NM: Los Alamos National Laboratory, 1989.

Asay, J.R.; Chhabildas, L.C.; Dandekar, D.P.
Shear Strength of Shock-Loaded Polycrystalline Tungsten.
Journal of Applied Physics, v51 n9, September 1980: 4774-4783.

Askins, D.; Bless, S.
Multi-Hit Ceramic Armor for .30APM2 (unclassified pages only).
In: TACOM Armor 4th Coordinating Conference. n.s., 1988: v2.

Askins, D.; Bless, S.
Multi-Hit Ceramic Armor for .30APM2.
In: TACOM Armor 4th Coordinating Conference, 1988: v2.

Azrin, Morris; Anctil, Albert A.; Kula, Eric B.
Dynamic Characterization of Intercritically Rolled High-Hardness
Steel: Final Report.
Watertown, MA: Army Materials and Mechanics Research Center, June
1982.

Azrin, Morris; Cowie, John G.; Olson, Gregory B.
Shear Instability Mechanisms in High Hardness Steel.
Watertown, MA: Army Materials Technology Laboratory, January 1987.

Backman, Marvin E.
Terminal Ballistics.
China Lake, CA: Naval Weapons Center, February 1976.

Barranger, John P.
Application of a Flight-Line Disk Crack Detector to a Small Engine.
In: An Assessment of Technology for Turbojet Engine Rotor Failures,
edited by Emmett A. Witmer. Cambridge, MA: Massachusetts Institute of
Technology, August 1977: 383-388.

Benck, Ralph F.; DiBerardo, Dominick A.
Quasi-Static Tensile Stress-Strain Curves--1, 2024-T3510 Aluminum
Alloy: Final Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory,
February 1976.

Bertholf, L.D.; Kipp, M.E.
Two-Dimensional Stress Wave Calculations of Kinetic Energy Projectile
Impact on Multi-Layered Targets.
Albuquerque, NM: Sandia Laboratories, n.d.

Bless, S.J.; Hartman, D.R.; Hanchak, S.J.
Ballistic Performance of Thick S-2 Glass Composites.
Presented at Composite Materials in Armament Applications Symposium.
Dover, NJ. August 20-22, 1985. Dayton, OH: University of Dayton Research
Institute Impact Physics Laboratory, n.d.

Bless, S.J.; Rondeau, R.A.; Askins, D.R.; Hanchak, S.J.; Jurick, D.L.
Ceramic Armor to Defeat Small Caliber Armor-Piercing Projectiles.
Wright-Patterson Air Force Base, OH: Wright Research and Development
Center, December 1989.

Bless, S.J.; Rosenberg, Z.; Yoon, B.
Hypervelocity Penetration of Ceramics.
n.s., n.d.

Bless, Stephan J.
Interior and Terminal Ballistics of 25g Long Rod Penetrators: Final
Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory,
April 1979.

Bloore, Ernest W.
The Metallurgy of Uranium in Ordnance Applications.
(In: Metallurgy Technology of Uranium and Uranium Alloys, Volume 3.
Gatlinburg, TN. May 26-28, 1981. Metals Park, OH: American Society for
Metals, 1982): 691-713.

Bollard, Roger J.H.
Characterization Requirements in Modeling Structural Ceramics.
American Ceramic Society Bulletin, v63 n2, February 1984: 253-255.

Booker, B.L.P.
Ceramic Technology for Advanced Heat Engines Project Data Base:
September 1988 Summary Report.
N.s.: Oak Ridge National Laboratory, September 1988.

Booker, M.K.
Ceramic Technology for Advanced Heat Engines Program Data Base: A
Summary Report.
N.s.: Oak Ridge National Laboratory, April 1988.

Boulet, J.A.M.
An Assessment of the State of the Art in Predicting the Failure of
Ceramics: Final Report.
Oak Ridge, TN: Oak Ridge National Laboratory, March 1988.

Brandon, D.G.; Ariel, E.; Barta, J.
Micromechanisms of Fracture in a W-5% Fe-5% Ni Powder Composite.
In: Electron Microscopy and Structure of Materials, edited by Gareth
Thomas, Richard M. Fulrath and Robert M. Fisher. Berkeley, CA: University of
California Press, (1971): 849-858.

Brandon, D.G.; Yeshurun, Y.
Mechanisms of Dynamic Failure in Debased Alumina.
n.s., n.d.

Brandon, D.G.; Yeshurun, Y.; Rosenberg, Z.; Ozeri, Y.
Micromechanisms of Impact Failure in Engineering Ceramics.
In: Macro- and Micro-Mechanics of High Velocity Deformation and
Fracture, edited by K. Kawata. Symposium in Toyko, Japan, August 12-15, 1985.
New York, NY: Springer-Verlag, (1987): 127-135.

Brantley, William A.
Microstructural and Fractographic Studies of Boron Carbide Subjected
to Ballistic Impact and Static Flexural Loading.
Watertown, MA: Army Materials and Mechanics Research Center, 1970.

Brar, N.S.; Bless, S.J.; Rosenberg, Z.
Brittle Failure of Ceramic Rods Under Dynamic Compression.
Journal de Physique, v49, September 1988: C3.607-C3.612.

Bretfeld, H.; Kleinlein, F.W.; Munz, D.; Pabst, R.F.; Richter, H.
Ermittlung des Bruchwiderstands an Oxidkeramik und Hartmetallen mit
verschiedenen Methoden.
Z. Werkstofftech, v12 n5, 1981: 167-174.

Bristow, R.J.; Herlin, W.M.
TASS Armor Analysis Methodology: Final Report.
Wright-Patterson Air Force Base, OH: Flight Dynamics Laboratory,
August 1988.

Brooks, P.N.
Ballistic Impact--The Dependence of the Hydrodynamic Transition
Velocity on Projectile Tip Geometry.
Valcartier, Canada: Department of National Defence, October 1974.

Brooks, P.N.; Erickson, W.H.
Ballistic Evaluation of Materials for Armour Penetrators.
Valcartier, Canada: Defence Research Establishment, November 1971.

Bruchey, W.J.; Horwath, E.J.; Kingman, P.W.
The Effect of Crystallographic Orientation on the Performance of
Single Crystal Tungsten Sub-Scale Penetrators: Interim Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory,
April 1990.

Bruchey, W.J.; Ricchiazzi, A.J.; Roecker, E.T.
Fibre-Reinforced Materials for High Density Penetrators.
In: Ballistics 6th International Symposium. Orlando, FL. October
27-29, 1981. n.s., American Defense Preparedness Association: 340-348.

Bruchey, William J.; Montiel, Denise M.
Mechanical Property Evaluation of a Series of Commercial Tungsten
Alloys.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, June
1987.

Budiansky, Bernard; O'Connell, Richard J.
Elastic Moduli of a Cracked Solid.
International Journal of Solids and Structures, v12 n2, 1976: 81-97.

Buresch, F.E.; Nickel, H.
Influence of Microstructure on the Failure Mechanisms and Toughness of
Ceramics.
In: High Tech Ceramics 6th International World Congress. Milan,
Italy. June 24-28, 1986. Amsterdam, Netherlands: Elsevier, 1987: 1209-1217.

Cagnoux, Jacques; Longy, Francois.
Is the Dynamic Strength of Alumina Rate-Dependent?
In: Shock Waves in Condensed Matter 1987, edited by S.C. Schmidt.
American Physical Society Topical Conference. Monterey, CA. July 20-23, 1987.
Amsterdam, Netherlands: North-Holland, 1988: 293-296.

Celens, E.
Summary of Results of Terminal Ballistics Research by the Royal
Military Academy (Belgium) Weapons and Ballistics Department.
Brussels, Belgium: Royal Military Academy, n.d.

Charalambides, P.G.; McMeeking, R.M.
Transformations, Microcracking and Toughening in Ceramics.
In: Constitutive Modeling for Nontraditional Materials, edited by
V.K. Stokes. New York, NY: American Society of Mechanical Engineers, 1987:
189-215.

Chhabildas, L.C.; Asay, J.R.; Barker, L.M.
Shear Strength of Tungsten Under Shock- and Quasi-Isentropic Loading
to 250 GPa (Gigapascal).
Albuquerque, NM: Sandia National Laboratories, April 1988.

Chilton, A.C.; Wronski, A.S.
The Effects of Strain Rate and Pressurization on the Ductile-Brittle
Transition Temperature of Polycrystalline Sintered Tungsten.
Journal of the Less-Common Metals, 17 n4, April 1969: 447-450.

Cline, C.F.; Wilkins, M.L.
The Importance of Material Properties in Ceramic Armor.
n.s., n.d.: 13-18.

Cook, Richard L.
Hard Faced Ceramic and Plastic Armor.
US Patent 3,509,833 (May 5, 1970).

Cook, Robert F.
Effect of Changes in Grain Boundary Toughness on the Strength of
Alumina.
In: Advanced Structural Ceramics Symposium. Boston, MA. December 1-3,
1986. Pittsburgh, PA: Materials Research Society, 1987: 199-206.

Cooke, R.G.
Microstructure and Failure Probability of Coarse Structured Ceramics.
In: British Ceramic Society 32nd Proceedings. London, UK. December
15-17, 1981. Shelton, UK: British Ceramic Society, March 1982: 171-180.

Costin, L.S.; Stone, C.M.
A Finite Element Material Model for Microfracture-Damaged Brittle
Rock.
Albuquerque, NM: Sandia National Laboratories, June 1987.

Curran, D.R.
Dependence of Non-Elastic Material Behavior on Microstructural
Processes.
n.s., February 1986.

Curran, Donald R.
Application of Micromechanical Failure Models to Shock Physics
Problems.
Menlo Park, CA: SRI International, n.d.

Dalgleish, B.J.; Rawlings, R.D.
A Comparison of the Mechanical Behavior of Aluminas in Air and
Simulated Body Environments.
Journal of Biomedical Materials Research, v15 n4, July 1981: 527-542.

Dalgleish, B.J.; Slamovich, E.; Evans, A.G.
High Temperature Failure of Ceramics.
Journal of Materials for Energy Systems, v8 n2, September 1986:
211-225.

Dastur, Y.N.; Leslie, W.C.
The Mechanism of Rapid Work Hardening in Hadfield Manganese Steel.
Presented at Strength of Metals and Alloys 5th International
Conference. Aachen, Germany. n.d. n.s., August 1979.

Davidge, R.W.
Combination of Fracture Mechanics, Probability, and Micromechanical
Models of Crack Growth in Ceramic Systems.
Metal Science, v14 n8/9, August/September 1980: 459-462.

Doherty, J.E.
NDE--A Key to Engine Rotor Life Prediction.
In: An Assessment of Technology for Turbojet Engine Rotor Failures,
edited by Emmett A. Witmer. Cambridge, MA: Massachusetts Institute of
Technology, August 1977: 369-382.

Dunleavy, J.G.; Duckworth, W.H., editors.
Ceramic-Armor Technology Symposium.
Ceramic-Armor Technology Symposium. Columbus, OH. January 29-30,
1969. n.s.: Defense Ceramic Information Center, May 1969.

Duttweiler, R.E.
Materials and Manufacturing Processes for Increased Life/Reliability.
In: An Assessment of Technology for Turbojet Engine Rotor Failures,
edited by Emmett A. Witmer. Cambridge, MA: Massachusetts Institute of
Technology, August 1977: 347-368.

Eisenmann, M.R.; German, R.M.
Factors Influencing Ductility and Fracture Strength in Tungsten Heavy
Alloys.
International Journal of Refractory and Hard Metals, v3 n2, June
1984: 86-91.

Ekbom, L.
The Influence of Microstructure of Liquid-Sintered Tungsten-Base
Composites on the Mechanical Properties.
Scandinavian Journal of Metallurgy, v5 n4, 1976: 179-184.

Ekbom, Lars B.
Keramer som Pansarmaterial (Ceramics as Armor Material).
Stockholm, Sweden: Forsvarets Forskningsanstalt, June 1989.

Ekbom, Lars.
Microstructural Study of the Deformation and Fracture Behavior of a
Sintered Tungsten-Base Composite.
In: Modern Developments in Powder Metallurgy: Volume 14 Special
Materials, edited by Henry H. Hausner. Princeton, NJ: Metal Powder Industries
Federation, American Powder Metallurgy Institute, n.d.: 177-188.

Ekbom, Lars; Bogegard, Sven; Holmberg, Lars: Westerling, Lars.
A Comparison of the Mechanical Properties of KE Penetrator Tungsten
Alloys and Their Ballistic Performance.
In: Ballistics 9th International Symposium. Shrivenham, UK. April
29-May 1, 1986. n.s., 1986: 2.447-2.456.

Ellingson, William A.; Vannier, Michael W.
X-Ray Computed Tomography for Nondestructive Evaluation of Advanced
Structural Ceramics.
Argonne, IL: Argonne National Laboratory, September 1988.

Erlich, D.C.; Seaman, L.; Cooper, T.; Caligiuri, R.D.; Curran, D.R.
Computational Model for Armor Penetration: Volume 1.
Menlo Park, CA: SRI International, 3rd annual, April 1983.

Erlich, D.C.; Seaman, L.; Curran, D.R.; Shockey, D.A.
A Preliminary Study of Armor Penetration by Shear Banding.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, July
1980.

Erlich, D.C.; Seaman, L.; Shockey, D.A.; Curran, D.A.
Development and Application of a Computational Shear Band Model: Final
Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory,
March 1980.

Evans, A.G.
A General Approach for the Statistical Analysis of Multiaxial
Fracture.
Journal of the American Ceramic Society, v61 n7/8, July/August 1978:
302-308.

Evans, A.G.
Engineering Property Requirements for High Performance Ceramics.
In: Engineering Ceramics 1984 International Symposium. Jerusalem,
Israel. December 16-20, 1984. Israel: Ministry of Science and Development,
1984: 3-21.

Evans, A.G.
Statistical Aspects of Cleavage Fracture in Steel.
Metallurgical Transactions A: Physical Metallurgy and Materials
Science, v14A n7, July 1983: 1349-1355.

Evans, A.G.
Structural and Microstructural Design in Brittle Materials.
In: Mechanical Behaviour of Materials 3rd International Conference.
Cambridge, UK. August 20-24, 1979. Oxford, UK: Pergamon Press, 1979: v1,
279-311.

Evans, A.G.; Drory, M.; Faber, K.T.; Hutchinson, J.; Kino, G.S.;
Khuri-Yakub, B.T.; Lamon, J.; Marshall, D.B.; Noma, T.; Ruf, H.; Tien, J.W.; U
Micro and Macro Mechanics of Fracture in Ceramics: Interim Report.
Arlington, VA: Office of Naval Research, October 30, 1982.

Evans, A.G.; Gulden, M.E.; Eggum, G.E.; Rosenblatt, M.
Impact Damage in Brittle Materials in the Plastic Response Regime:
Technical Report.
Arlington, VA: Office of Naval Research, 1976.

Evans, A.G.; Meyer, M.E.; Fertig, K.W.; Davis, B.I.; Baumgartner,
H.R.
Probabilistic Models for Defect Initiated Fracture in Ceramics.
Journal of Nondestructive Evaluation, v1 n2, June 1980: 111-122.

Evans, A.G.; Richerson, D.W.
Failure Analysis of Ceramics.
In: Encyclopedia of Materials Science and Engineering Volume 3,
edited by Michael B. Bever. Oxford, UK: Pergamon Press, n.d.: 1619-1625.

Evans, A.G.; Ruhle, M.; Turwitt, M.
On the Mechanics of Failure in Ceramic/Metal Bonded Systems.
Journal de Physique, v46, April 1985: C4.613-C4.626.

Ferguson, W.J.; Rice, R.W.
Effect of Microstructure on the Ballistic Performance of Alumina.
Washington, DC: Naval Research Laboratory, August 1971.

Ferguson, W.J.; Rice, R.W.
Effect of Microstructure on the Ballistic Performance of Alumina.
In: Materials Science Research, edited by W. Wurth Kriegel. New York,
NY: Plenum Press, 1971: v5, 261-270.

Florence, A.L.
Interaction of Projectiles and Composite Armor: Part 2 (Final Report).
Watertown, MA: Army Materials and Mechanics Research Center, August 1969.

Florence, A.L.; Ahrens, T.J.
Interaction of Projectiles and Composite Armor: Final Report.
Watertown, MA: Army Materials Research Agency, January 31, 1967.

Forrestal, M.J.; Rosenberg, Z.; Luk, Y.K.; Bless, S.J.
Perforation of Aluminum Plates with Conical-Nosed Rods.
Journal of Applied Mechanics, v54 n1, March 1987.

Frank, Konrad.
Armor-Penetrator Performance Measures: Final Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, March 1981.

Franz, Robert E.; Robitaille, Joseph L.
The Hugoniot of 4340 Steel RC 54-55.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, March 1978.

Frechette, V.D.; Cline, C.F.
Fractography of Ballistically Tested Ceramics.
American Ceramic Society Bulletin, v49 n11, November 1970: 994-997.

Gardner, P.B.
Ceramic Composite Protection for Turbine Disc Bursts.
n.s., n.d.: 277-293.

Gardner, P.B.
Ceramic Composite Protection for Turbine Disc Bursts.
In: An Assessment of Technology for Turbojet Engine Rotor Failures,
edited by Emmett A. Witmer. Cambridge, MA: Massachusetts Institute of
Technology, August 1977: 277-293.

Gee, M.G.; Cox, J.M.
The Response of Ceramics to Repeated Impact Loads.
In: Institute of Ceramics Basic Science Section Meeting. London, UK.
December 18-20, 1985. Institute of Ceramics, 1985: v37, 207-216.

Gerlach, Uwe.
Microstructural Analysis of Residual Projectiles--A New Method to
Explain Penetration Mechanisms.
Metallurgical Transactions, v17A n3, March 1986: 435-442.

German, R.M.
Microstructure Limitations of High Tungsten Content Heavy Alloys.
In: Plansee 11th International Seminar 1985. Reutte, Austria. May
20-24, 1985. n.s., 1985: v1, 143-161.

German, R.M.; Hanafee, J.E.; DiGiallonardo, S.L.
Toughness Variation With Test Temperature and Cooling Rate for Liquid
Phase Sintered W-3.5Ni-1.5Fe.
Metallurgical Transactions A, v15A, January 1984: 121-128.

Gerstle, J.H.
Analysis Methods for Kevlar Shield Response to Rotor Fragments.
In: An Assessment of Technology for Turbojet Engine Rotor Failures,
edited by Emmett A. Witmer. Cambridge, MA: Massachusetts Institute of
Technology, August 1977: 261-275.

Gielisse, P.J.; Choudry, A.; Kim, T.
Dynamic and Material Parameters in Brittle Fracture in Ceramics.
In: Materials Science Research Volume 11: Processing of Crystalline
Ceramics, edited by Hayne Palmour. New York, NY: Plenum Press, n.d.: 285-302.

Giovanola, Jacques H.
Adiabatic Shear Banding Under Pure Shear Loading: Part 1 Direct
Observation of Strain Localization and Energy Dissipation Measurements.
Mechanics of Materials, v7, 1988: 59-71.

Giovanola, Jacques H.
Adiabatic Shear Banding Under Pure Shear Loading: Part 2 Fractographic
and Metallographic Observations.
Mechanics of Materials, v7, 1988: 73-87.

Glenn, L.A.; Gommerstadt, B.Y.; Chudnovsky, A.
A Fracture Mechanics Model of Fragmentation.
Journal of Applied Physics, v60 n3, August 1, 1986: 1224-1226.

Goddard, Stanley.
Selection of a Kinetic-Energy Threat for Light-Armor Developers.
In: TACOM Armor 3rd Coordinating Conference for Light Combat
Vehicles. n.s., 1987: v1.

Gogotsi, G.A.
The Use of Brittleness Measure (x) to Represent Mechanical Behaviour
of Ceramics.
Ceramics International, v15 n2, 1989: 127-129.

Goldsmith, Werner; Finnegan, S.A.
Penetration and Perforation Processes in Metal Targets At and Above
Ballistic Velocities.
International Journal of Mechanical Science, v13 n10, October 1971:
843-866.

Grady, D.
The Mechanics of Fracture Under High-Rate Stress Loading.
In: Mechanics of Geomaterials: Rocks, Concretes, Soils, edited by
Zdenek P. Bazant. Chichester, UK: John Wiley and Sons, Ltd., 1985: 129-156.

Gust, W.H.; Holt, A.C.; Royce, E.B.
Dynamic Yield, Compressional, and Elastic Parameters for Several
Lightweight Intermetallic Compounds.
Journal of Applied Physics, v44 n2, February 1973: 550-560.

Gust, W.H.; Royce, E.B.
Dynamic Yield Strengths of B4C, BeO, and Al2O3 Ceramics.
Journal of Applied Physics, v42 n1, January 1971: 276-295.

Gyekenyesi, John P.
SCARE--A Post-Processor Program to MSC/NASTRAN for the Reliability
Analysis of Structural Ceramic Components.
Washington, DC: National Aeronautics and Space Administration, 1986.

Halverson, Danny C.; Pyzik, Aleksander J.; Aksay, Ilhan A.; Snowden, William E.
Processing of Boron Carbide-Aluminum Composites.
Journal of the American Ceramic Society, v72 n5, May 1989: 775-780.

Hansen, John V.E.
Processing Success Story: Boron Carbide Body Armor.
Metal Progress, v95 n2, February 1969: 111-113.

Harding, J.; Huddart, J.
The Use of the Double-Notch Shear Test in Determining the Mechanical Properties of Uranium at Very High Rates of Strain.
In: Mechanical Properties of Materials at High Rates of Strain 2nd Conference. Oxford, UK. March 28-30, 1979. Bristol, UK: Institute of Physics, 1980: 49-61.

Hauver, George E.
The Alpha-Phase Hugoniot of Rolled Homogeneous Armor.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, August 1976.

Hauver, George E.
The Hugoniot for 90W-7Ni-3Fe Tungsten Alloy.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, May 1978.

Hauver, George E.
The Hugoniot for 90W-7Ni-3Fe Tungsten Alloy: Final Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, February 1980.

Heard, H.C.; Cline, C.F.
Mechanical Behaviour of Polycrystalline BeO, Al2O3 and AlN at High
Pressure.
Journal of Materials Science, v15 n8, August 1980: 1889-1897.

Herr, Louis; Grabarek, Chester.
Ballistic Performance and Beyond Armor Data for Rods Impacting Steel
Armor Plates: Final Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory,
January 1976.

Hickey, Charles F.; Anctil, Albert A.
Split Heat Mechanical Property Comparison of ESR and VAR 4340 Steel:
Final Report.
Watertown, MA: Army Materials and Mechanics Research Center, May
1983.

Hickey, Charles F.; Anctil, Albert A.; Chait, Richard.
The Ballistic Performance of the High Strength 4340 Steel Processed By
Electroslag Remelting.
Watertown, MA: Army Materials and Mechanics Research Center,
September 1981.

Hickey, Charles F.; Thomas, Timothy S.; Anctil, Albert A.
Comparison of Ballistic Performance of a Split Heat of ESR and VAR
4340 Steel.
Watertown, MA: Army Materials and Mechanics Research Center, July
1985.

Hill, J.T.
Design of Rotors for Improved Structural Life.
In: An Assessment of Technology for Turbojet Engine Rotor Failures,
edited by Emmett A. Witmer. Cambridge, MA: Massachusetts Institute of
Technology, August 1977: 331-346.

Hohler, V.; Stilp, A.
Influence of the Length-to-Diameter Ratio in the Range From 1 to 32 on
the Penetration Performance of Rod Projectiles.
In: Ballistics 8th International Symposium. Orlando, FL. October
23-25, 1984. Wilmington, MA: Avco Systems Division, 1984: IB13-20.

Hohler, V.; Stilp, A.J.
Penetration of Steel- and High Density Rods in Semi-Infinite Steel
Targets.
In: Ballistik 1977 Internationales Symposium. Karlsruhe, Germany.
March 23-25, 1977. Karlsruhe, Germany: Institut fur Chemie der Trieb-und
Explosivstoffe, 1977: 1-12.

Holms, Arthur G.
Concepts for the Development of Light-Weight Composite Structures for
Rotor Burst Containment.
In: An Assessment of Technology for Turbojet Engine Rotor Failures,
edited by Emmett A. Witmer. Cambridge, MA: Massachusetts Institute of
Technology, August 1977: 295-330.

Horii, H.; Nemat-Nasser, S.
Compression-Induced Microcrack Growth in Brittle Solids: Axial
Splitting and Shear Failure.
Journal of Geophysical Research, v90 nB4, March 10, 1985: 3105-3125.

Horii, H.; Nemat-Nasser, S.
Overall Moduli of Solids With Microcracks: Load-Induced Anisotropy.
Journal of the Mechanics and Physics of Solids, v31 n2, 1983:
155-171.

Howe, Carol Sandberg.
New Ceramic Material Gives Champion Performance.
Ceramic Industry, v127 n5, October 1986: 34-36.

Hull, J.L.; Daniels, N.H.G.
Improved Composite Armor Produced by Impulse Resistance Sintering:
Final Report.
Watertown, MA: Army Materials and Mechanics Research Center, October
1971.

Hutchings, I.M.
The Behaviour of Metals Under Ballistic Impact at Sub-Ordnance
Velocities.
In: Material Behavior Under High Stress and Ultrahigh Loading Rates,
edited by John Mescall and Volker Weiss. New York, NY: Plenum Press, n.d.:
161-196.

Irwin, G.J.
Metallographic Interpretation of Impacted Ogive Penetrators.
Quebec, Canada: Defence Research Establishment, October 1972.

Iseki, T.; Yano, T.
Brazing of SiC Ceramics With Active Metal.
In: International Ceramic Conference Austercam 88. Sydney, Australia.
August 21-26, 1988. Switzerland: Transtech Publications, 1988: v1, 421-425.

Johnson, D. Ray; Morgan, P.E.D.
Ceramic Matrix Composites as Armor Materials.
Wright-Patterson Air Force Base, OH: Air Force Materials Laboratory,
April 1970.

Johnson, G.R.
Dynamic Analysis of Explosive-Metal Interaction in Three Dimensions.
Journal of Applied Mechanics, v48 n1, March 1981: 30-34.

Johnson, G.R.; Stryk, R.A.
User Instructions for the EPIC-3 Code: Final Report.
Eglin Air Force Base, FL: Air Force Armament Laboratory, May 1987.

Johnson, Gordon R.; Stryk, Robert A.; Nixon, Michael E.
Two- and Three-Dimensional Computational Approaches for Steel
Projectiles Impacting Concrete Targets.
Presented at Post-SMIRT Seminar on Impact. Lausanne, Switzerland.
August 1987. n.s., n.d.

Johnson, Peter K.
Tungsten Versus Depleted Uranium for Armour-Piercing Penetrators.
International Journal of Refractory and Hard Metals, December 1983:
179-182.

Joint Technical Coordinating Group for Aircraft Survivability.
Design of Armor Systems 1983 Conference (U): Volume 1 Unclassified
Papers.
Design of Armor Systems 1983 Conference (U). Monterey, CA. April 19-
21, 1983. Washington, DC: Naval Air Systems Command, October 1983.

Jonas, G.H.; Zukas, J.A.
Mechanics of Penetration: Analysis and Experiment.
International Journal of Engineering Science, v16 n11, 1978: 879-903.

Kanazawa, Takeshi; Oba, Hiroshi; Machida, Susumu.
The Effect of Welding Residual Stress on Brittle Fracture Propagation.
Journal of Zosen Kiokai, v109, June 1961: 359-369.

Kaneko, Takeshi.
Effect of Heat Treatment on Dynamic Mechanical Properties of W-Ni-Fe
Heavy Alloys.
Journal of the Japan Society of Powder and Powder Metallurgy, v36 n1,
February 1989: 43-48.

Kaneko, Takeshi.
Fracture Toughness of W-Ni-Fe Heavy Alloys.
Journal of the Japan Society of Powder and Powder Metallurgy, v35 n8,
November 1988: 757-762.

Katz, Allan P.; Kerans, Ronald J.
Structural Ceramics Program at AFWAL Materials Lab.
American Ceramic Society Bulletin, v67 n8, August 1988: 1360-1366.

Katz, R. Nathan.
High-Temperature Structural Ceramics.
Science, v208, May 23, 1980: 841-847.

Katz, R. Nathan; Brantley, William A.
Fractography of High Boron Ceramics Subjected to Ballistic Loading.
In: Materials Science Research: Ceramics in Severe Environments,
edited by W. Wurth Kriegel. New York, NY: Plenum Press, 1971: v5, 271-282.

Kaufman, Albert.
Turbine Disks for Improved Reliability.
In: An Assessment of Technology for Turbojet Engine Rotor Failures,
edited by Emmett A. Witmer. Cambridge, MA: Massachusetts Institute of
Technology, August 1977: 389-411.

Kennedy, C.M.; Ofstedahl, K.E.; Mayseless, M.
Analysis of Impacts on Alumina.
In: TACOM Armor 3rd Coordinating Conference for Light Combat
Vehicles. n.s., 1987: v2, 411-424.

Keyes, B.L.P.
Ceramic Technology for Advanced Heat Engines Project Data Base: March
1989 Summary Report.
Oak Ridge, TN: Oak Ridge National Laboratory, June 1989.

Kim, Chong Hee; Palmour, H.
Microstructural Alterations in Alumina Ceramics Associated With
Ballistic Impact Events: Technical Report.
Raleigh, NC: North Carolina State University, December 1970.

Kipp, M.E.; Grady, D.E.; Chen, E.P.
Strain-Rate Dependent Fracture Initiation.
International Journal of Fracture, v16 n5, October 1980: 471-478.

Kipp, Marlin E.; Grady, Dennis E.
Numerical Studies of Rock Fragmentation.
n.s., n.d.

Knauss, W.G.; Dempsey, J.P.; Freund, L.B.; Hahn, H.T.; Kobayashi,
A.S.; Mescall, J.F.; Nash, W.A.
Soviet Dynamic Fracture Mechanics Research.
McLean, VA: Science Applications International Corp., February 1988.

Kosachev, L.S.; Kurdyumova, G.G.; Milman, Y.V.; Pushkin, V.F.;
Rymashevskii, G.A.; Khomenko, G.E.
A Study of Fracture Mechanism in Low-Concentration Tungsten-Base
Alloys in Prestrained State.
Physics of Metals, v6 n2, October 1985: 264-277.

Kostava, A.A.; Murav'yev, V.K.
High Temperature Hydrostatic Extrusion of Metals and Alloys.
Kuznechno-Shtampovochnoye Proizvodstvo, n1, 1977: 9-11.

Kriegel, W. Wurth; Palmour, Hayne, editors.
Materials Science Research: Ceramics in Severe Environments (Preface
and Table of Contents only).
New York, NY: Plenum Press, 1971: v5.

Krock, Richard H.; Shepard, Lawrence A.
Mechanical Behavior of the Two-Phase Composite, Tungsten-Nickel-Iron.
Transactions of the Metallurgical Society of AIME, v227 n5, October
1963: 1127-1134.

Kunze, H.D.; Meyer, L.W.
Materials for Extreme Dynamic Loads.
In: Metallurgical Applications of Shock-Wave and High-Strain-Rate
Phenomena, edited by Lawrence E. Murr. New York, NY: Marcel Dekker, Inc.,
n.d.: 481-507.

Kunze, Hans-Dieter; Hartmann, Karl-Heinz; Rickel, Jurgen.
Revealing the Structure of Severely Work Hardened Shear Zones.
Practical Metallography, v18, June 1981: 261-270.

Lambert, J.P.; Jonas, G.H.
Towards Standardization in Terminal Ballistics Testing: Velocity
Representation (Final Report).
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory,
January 1976.

Lambert, J.P.; Ringers, B.E.
Standardization of Terminal Ballistics Testing, Data Storage and
Retrieval: Final Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, May
1978.

Lambert, John P.
The Terminal Ballistics of Certain 65 Gram Long Rod Penetrators
Impacting Steel Armor Plate: Final Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, May
1978.

Lambropoulos, J.C.
Macroscopic and Microscopic Localization of Deformation in
Transformation-Toughened Ceramics.
In: Constitutive Modeling for Nontraditional Materials, edited by
V.K. Stokes. New York, NY: American Society of Mechanical Engineers, 1987:
217-232.

Lamicq, Pierre J.; Bernhart, Gerald A.; Dauchier, Martine M.; Mace,
Jean G.
SiC/SiC Composite Ceramics.
American Ceramic Society Bulletin, v65 n2, January 1986: 336-338.

Lamon, Jacques.
Statistical Approaches to Failure for Ceramic Reliability Assessment.
Journal of the American Ceramic Society, v71 n2, February 1988:
106-112.

Landingham, R.L.; Casey, A.W.
Final Report of the Light Armor Materials Program.
Livermore, CA: Lawrence Livermore Laboratory, September 15, 1972.

Landingham, R.L.; Casey, A.W.
Semiannual Progress Report of the Light-Armor Materials Program.
Livermore, CA: Lawrence Radiation Laboratory, June 9, 1971.

Lankford, James.
Compressive Strength and Damage Mechanisms in Ceramic Materials:
Interim Technical Report.
San Antonio, TX: Southwest Research Institute, September 1980.

Lankford, James.
Compressive Strength and Microplasticity in Polycrystalline Alumina.
Journal of Materials Science, v12 n4, April 1977: 791-796.

Lawn, Brian R.
Physics of Fracture.
Journal of the American Ceramic Society, v66 n2, February 1983:
83-91.

Lazarev, V.B.; Shevchenko, V.Y.; Zhavoronkov, N.M.; Izotov, A.D.
Physico-Chemical Model of Destruction of Ceramics Under High Speed
Deformation.
In: Science of Hard Materials 1984 International Conference. Rhodes,
Greece. September 23-28, 1984. Bristol, UK: Adam Hilger, Ltd., 1984: 439-447.

Lee, Minyoung; Brun, Milivoj K.
Fracture Toughness Measurement by Microindentation and Three-Point
Bend Methods.
In: Materials Science and Engineering, A--Structural Materials:
Properties, Microstructure and Processing, vA105/106, 1988: 369-375.

Liaw, B.M.; Kobayashi, A.S.; Emery, A.F.
Theoretical Model of Impact Damage in Structural Ceramics.
Journal of the American Ceramic Society, v67 n8, August 1984:
544-548.

Lindholm, Ulric S.; Johnson, Gordon R.
Strain-Rate Effects in Metals at Large Shear Strains.
In: Material Behavior Under High Stress and Ultrahigh Loading Rates,
edited by John Mescall. New York, NY: Plenum Press, n.d.: 61-79.

Lips, H.R.; Weisshaupt, H.P.; Niemeyer, T.W.
Dynamic Behaviour and Properties of Heavy Metals--Experimental
Approach to Separation of Parameters in the Johnson-Cook Constitutive Model.
n.s., n.d.

Long, William D.; Brantley, William A.
Fractographic Analyses of Ceramics and Glass-Ceramics Subjected to
Ballistic Impact.
American Ceramic Society Bulletin, v50 n8, August 1971: 662-665.

Lu, Mei-Chien.
On Mechanical Behavior of Metal-Ceramic Bonded Systems: Dissertation.
Berkeley, CA: Lawrence Berkeley Laboratory, April 1987.

Luhleich, Hartmut; Dias, Francisco J.
Method of Producing Composite Armor Plate Bodies.
US Patent 4,604,249 (August 5, 1986).

Mach, H.
Oberflachentemperatur von Stabgeschossen nach Durchschlagen einer
Panzerplatte. (Surface Temperature of Rodshaped Projectiles After Perforating
an Armor Plate).
St. Louis, France: Institut Franco-Allemand de Recherches, 1975.

Manderscheid, Jane M.; Gyekenyesi, John P.
Fracture Mechanics Concepts in Reliability Analysis of Monolithic
Ceramics.
Washington, DC: National Aeronautics and Space Administration, 1987.

Mariano, Stephen A.; Prifti, Joseph J.
Development of Armor Systems to Defeat Advanced Threats (unclassified
pages only).
n.s.: Army Laboratory Command, n.d.

Marshall, D.; Cox, B.N.; Oliver, W.C.; Evans, A.G.
Fiber Matrix Interface Effects in Failure of Ceramic Matrix Fiber
Composites: Annual Report.
Arlington, VA: Office of Naval Research, October 1986.

Marshall, D.B.; Evans, A.G.
Failure Mechanisms in Ceramic-Fiber/Ceramic-Matrix Composites.
Journal of the American Ceramic Society, v68 n5, May 1985: 225-231.

Marshall, David B.; Ritter, John E.
Reliability of Advanced Structural Ceramics and Ceramic Matrix
Composites--A Review.
American Ceramic Society Bulletin, v66 n2, February 1987: 309-317.

Mayseless, M.; Goldsmith, W.; Virostek, S.P.; Finnegan, S.A.
Impact on Ceramic Targets.
Journal of Applied Mechanics, v54 n2, June 1987: 373-378.

Mayseless, M.; Goldsmith, W.; Virostek, S.P.; Finnegan, S.A.;
Kennedy, C.M.; Ofstedahl, K.E.
Impact on Alumina.
In: Impact Loading and Dynamic Behaviour of Materials, edited by C.Y.
Chien. Oberursel, Germany: DGM Informationalsgesellschaft mit beschrankter
Haftung, (1988): v1, 407-414.

McClintock, Frank A.
Statistics of Brittle Failure.
In: Fracture Mechanics of Ceramics Volume 1 Concepts, Flaws and
Fractography, edited by R.C. Bradt. New York, NY: Plenum Press, n.d.: 93-114.

McHenry, K.D.; Koepke, B.G.; Johnson, G.R.; Lambert, L.W.
Advanced Applique Armor (unclassified pages only).
In: TACOM Armor 3rd Coordinating Conference for Light Combat
Vehicles. n.s., 1987: v1, 208, 210, 230.

McHenry, K.D.; Stokes, R.J.; Stelzer, E.L.
Dynamic Fracture Properties of Ceramics Subjected to Impulsive
Loading: Proposal to the US Army Research Office.
Bloomington, MN: Honeywell Corporate Technology Center, n.d.

McMillan, P.W.; Tesh, J.R.
Dynamic Effects in the Impact Testing of Brittle Materials.
Journal of Materials Science, v10 n4, April 1975: 621-632.

McQueen, R.G.; Marsh, S.P.; Taylor, J.W.; Fritz, J.N.; Carter, W.J.
The Equation of State of Solids From Shock Wave Studies.
In: High-Velocity Impact Phenomena, edited by Ray Kinslow. New York,
NY: Academic Press, 1970: 293-417.

Mescall, John F.; Tracy, Carl.
Improved Modeling of Fracture in Ceramic Armors.
In: Army Science 1986 Conference Proceedings. June 17-19, 1986. n.s.;
Department of the Army, 1986: v3, 41-53.

Mescall, John.
Ceramic Tile Size Effects in Ceramic Armors.
n.s., n.d.

Meyer, Lothar W.; Kunze, Hans D.; Staskewitsch, Ewald.
Dynamic Strength and Ductility of a Tungsten-Alloy for KE-Penetrators
in Swaged and Unswaged Condition Under Various Loading.
In: Ballistics 7th International Symposium. The Hague, Netherlands.
April 19-21, 1983. n.s., 1983: 289-293.

Miller, Richard T.
The TACOM/DARPA Automated Armor Database System.
In: TACOM Armor 3rd Coordinating Conference for Light Combat
Vehicles. n.s., 1987: v1, 129-138.

Misey, John.
Analysis of Ballistic Limit: Final Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory,
March 1978.

Morelli, John J.
Some Airline Experience in Preventing Engine Rotor Failures.
In: An Assessment of Technology for Turbojet Engine Rotor Failures,
edited by Emmett A. Witmer. Cambridge, MA: Massachusetts Institute of
Technology, August 1977: 413-424.

Morfogenis, Peter G.
A Learning Curve Type Equation Predicting Residual Velocity.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory,
April 1975.

Morris, B.
Ballistic Evaluation of Advanced Armors Against Long Rod and EFP
Projectiles (unclassified pages only).
In: TACOM Armor 3rd Coordinating Conference for Light Combat
Vehicles. n.s., 1987: v2, 158-162, 166, 171.

Munson, D.E.; Lawrence, R.J.
Dynamic Deformation of Polycrystalline Alumina.
Journal of Applied Physics, v50 n10, October 1979: 6272-6282.

Murray, E. Allen.
Quasi-Static Compression Stress-Strain Curves-2, Results for 7039
Aluminum: Final Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory,
February 1976.

Muzychenko, V.P.; Postnov, V.I.
Comparative Tests cn Materials in High-Speed Impact With Penetration
(Review).
Industrial Laboratory, v52 n5, May 1986: 463-472.

Ness, E.A.; Hoffman, R.J.; Haney, C.N.; Rafaniello, W.; Moffett, K.
Effect of Porosity on the Ballistic Performance of Boron Carbide Armor
Tiles.
Midland, MI: Dow Chemical Co., (1989).

Netherwood, Paul H.
Rate of Penetration Measurements: Final Report.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory,
December 1979.

Nicholas, T.
Dynamic Tensile Testing of Structural Materials Using a Split
Hopkinson Bar Apparatus: Interim Report January 1973-December 1979.
Wright-Patterson Air Force Base, OH: Air Force Materials Laboratory,
October 1980.

Nicholas, Theodore.
Tensile Testing of Materials at High Rates of Strain.
Experimental Mechanics, v21 n5, May 1981: 177-185.

Nobbe, Thomas A.
Armor Goes Hi-Tech: In Applications Ranging from Massive Tanks to
Bullet-Proof Vests, Lightweight Armor Based on Advanced Composites and
Ceramics Is Rapidly Becoming the State of the Art in Ballistics Protection.
Materials Engineering, v103 n6, June 1986: 30-33.

Norris, D.M.; Scudder, J.K.; McMaster, W.H.; Wilkins, M.L.
Mechanics of Long-Rod Penetration at High Angles of Obliquity.
Presented at High Density Alloy Penetrator Materials 1976 Conference.
Charlottesville, VA. May 24-27, 1976. Livermore, CA: Lawrence Livermore
Laboratory, May 20, 1976.

O'Neil, Joseph W.; Salyer, Phillip N.
Effect of Tungsten Composition on the Mechanical Properties on the
W-Ni-Fe Heavy Alloy.
n.s.: Air Force Office of Scientific Research, December 1965.

Oakes, R.E.; Moyer, M.W.
A Review of Techniques Used to Characterize Cemented Tungsten Alloys
for Penetrator Applications.
Oak Ridge, TN: Energy Research and Development Administration,
September 28, 1977 (Incomplete).

Ogorkiewicz, R.M.
Armoured Vehicles of Composite Materials.
International Defense Review, v22, July 1989: 969-970.

Oh, S.Y.; Cornie, J.A.; Russell, K.C.
Particulate Wetting and Metal: Ceramic Interface Phenomena.
Ceramic Engineering and Science Proceedings, July/August 1987:
912-936.

Olson, G.B.; Mescall, J.F.; Azrin, M.
Adiabatic Deformation and Strain Localization.
In: Shock Waves and High-Strain-Rate Phenomena in Metals: Concepts
and Applications, edited by Marc A. Meyers and Lawrence E. Murr. New York,
NY: Plenum Press, n.d.: 221-247.

Orange, G.; Liang, K.M.; Fantozzi, G.
Crack Resistance and Fracture Toughness of Alumina and Zirconia
Ceramics: Comparison of Notched-Beam and Indentation Techniques.
In: Science of Ceramics 14, edited by Derek Taylor. Stoke-on-Trent,
UK: Institute of Ceramics, 1988: 709-714.

Ortiz, M.
A Continuum Theory of Crack Shielding in Ceramics.
Journal of Applied Mechanics, v54 n1, March 1987: 54-58.

Osborn, John J.
Improvements in EPIC3-Link to Hull, Improved Equation-of-State,
Improved Fracture Modelling, SAIL Update System, Other Improvements.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, June
1981.

Ostermann, Friedrich G.
On the Effects of Annealing and Grain Size in Powder-Metallurgy
Tungsten.
Wright-Patterson Air Force Base, OH: Air Force Materials Laboratory,
September 1963.

Palmour, H.; Johnson, D.R.; Kim, C.H.; Zimmer, C.E.
Fractographic and Thermal Analyses of Shocked Alumina.
n.s.: Office of Naval Research, April 1969.

Parilak, L.; Dusza, J.; Slesar, M.; Skopek, K.
Mechanical Properties of Ceramics Based on Al2O3.
In: Science of Ceramics 14, edited by Derek Taylor. Shelton, UK:
Institute of Ceramics, n.d.: 703-708.

Penrice, T.W.
Developments in Materials for Use as Kinetic Energy Penetrators.
In: Powder Metallurgy in Defense Technology. Yuma, AZ. November
13-14, 1979. Princeton, NJ: Metal Powder Industries Federation, 1980: 11-21.

Penrice, T.W.
Tungsten and Depleted Uranium for Kinetic Energy Penetrators.
n.s., n.d.: 140-150.

Penrice, Thomas W.
Refractory Metals in Ordnance.
In: Powder Metallurgy 1983 Annual Conference. New Orleans, LA. May
1-4, 1983. Princeton, NJ: Metal Powder Industries Federation, 1984: 507-513.

Phillips, D. Clive; Park, Nicholas; Lee, Richard J.; Preston, Roy F.;
Dawson, David M.
The Behavior of Ceramic Matrix, Fiber Composites Under Combined Impact
and Tensile Stresses: Final Report.
Wright-Patterson Air Force Base, OH: Air Force Wright Aeronautical
Laboratories, May 1988.

Piller, R.C.; Balkwill, K.P.; Briggs, A.; Davidge, R.W.
Mechanical Properties of Alumina Ceramics Prepared from High Purity
Powders.
In: Institute of Ceramics Basic Science Section Meeting. London, UK.
December 18-20, 1985. Institute of Ceramics, 1985: v37, 191-205.

Pletka, B.J.; Wiederhorn, S.M.
A Comparison of Failure Predictions by Strength and Fracture Mechanics
Techniques.
Journal of Materials Science, v17 n5, May 1982: 1247-1268.

Quinn, G.D.
Review of Static Fatigue in Silicon Nitride and Silicon Carbide.
In: Ceramic Engineering and Science Proceedings. Cape Cod, MA.
October 5-6, 1981. Columbus, OH: American Ceramic Society, 1982: 77-98.

Rabin, Barry H.; Bose, Animesh; German, Randall M.
Characteristics of Liquid Phase Sintered Tungsten Heavy Alloys.
International Journal of Powder Metallurgy, v25 n1, 1989: 21-27.

Rafaniello, W.
BTI Dow Chemical Aluminum Nitride Data.
Correspondence from W. Rafaniello to Stephen P. Andrew. Midland, MI:
Dow Chemical Co., January 10, 1990.

Rafaniello, W.; Brubaker. B.; Hoffman, R.
Evaluation of Low-Cost Aluminum Nitride Armor Tiles.
Midland, MI: Dow Chemical Co., (1989).

Rajendran, A.M.; Cook, W.H.
A Comprehensive Review of Modeling of Impact Damage in Ceramics: Final
Report.
Eglin Air Force Base, FL: Air Force Armament Laboratory, December
1988.

Rajendran, A.M.; Nicholas, T.
Dynamic Constitutive/Failure Models: Final Report.
Wright-Patterson Air Force Base, OH: Air Force Wright Aeronautical
Laboratories, December 1988.

Recht, R.F.
Catastrophic Thermoplastic Shear.
Journal of Applied Mechanics: Series E, v31 n2, June 1964: 189-193.

Rice, R.W.
Failure Initiation in Ceramics: Challenges to NDE and Processing.
In: Ceramic 1988 International Conference. Sydney, Australia. August
21-26, 1988. Switzerland: Trans Tech Publications, 1988: 1057-1064.

Rice, R.W.
Machining Flaws and the Strength Grain Size Behavior of Ceramics.
Washington, DC: Naval Research Laboratory, September 28, 1979.

Rice, R.W.; Freiman, S.W.; Pohanka, R.C.; Mecholsky, J.J.; Wu, C.C.
Microstructural Dependence of Fracture Mechanics: Parameters in
Ceramics.
In: Fracture Mechanics of Ceramics: Volume 4 Crack Growth and
Microstructure, edited by R.C. Bradt. New York, NY: Plenum Press, n.d.:
849-876.

Ritter, John E.; Fahey, John P.; Duffy, Peter L.
Slow-Stressing-Rate Testing of Ceramic Materials.
American Ceramic Society Bulletin, v63 n12, December 1984: 1517-1518.

Rogers, H.C.
Adiabatic Shearing--General Nature and Material Aspects.
In: Material Behavior Under High Stress and Ultrahigh Loading Rates,
edited by John Mescall and Volker Weiss. New York, NY: Plenum Press, n.d.:
101-118.

Rogers, H.C.; Shastry, C.V.
Material Factors in Adiabatic Shearing in Steels.
In: Shock Waves and High-Strain-Rate Phenomena in Metals: Concepts
and Applications, edited by Marc A. Meyers and Lawrence E. Murr. New York,
NY: Plenum Press, n.d.: 285-298.

Rogers, Harry C.
Adiabatic Plastic Deformation.
Annual Review of Material Science, v9, 1979: 283-311.

Rosenberg, Z.
Dynamic Uniaxial Stress Experiments on Alumina With In-Material
Manganin Gauges.
Journal of Applied Physics, v57 n11, June 1, 1985: 5087-5088.

Rosenberg, Z.; Bless, S.J.; Yeshurun, Y.; Okajima, K.
A New Definition of Ballistic Efficiency of Brittle Materials Based on
the Use of Thick Backing Plates.
In: Impact loading and Dynamic Behaviour of Materials, edited by C.Y.
Chien. Oberursel, Germany: DGM Informationsgesellschaft mit beschrankter
Haftung, (1988): 491-498.

Rosenberg, Z.; Forrestal, M.J.
Perforation of Aluminum Plates with Conical-Nosed Rods: Additional
Data and Discussion.
Journal of Applied Mechanics, v55, March 1988: 236-238.

Rosenberg, Z.; Yeshurun, Y.
Determination of the Dynamic Response of AD-85 Alumina With
In-Material Manganin Gauges.
Journal of Applied Physics, v58 n8, October 15, 1985: 3077-3080.

Rosenberg, Z.; Yeshurun, Y.
The Relation Between Ballistic Efficiency and Compressive Strength of
Ceramic Tiles.
International Journal of Impact Engineering, v7 n3, 1988: 357-362.

Rosenberg, Z.; Yeshurun, Y.; Brandon, D.C.
Dynamic Response and Microstructure of Commercial Alumina.
Journal de Physique, v46, August 1985: C5.331-C5.341.

Rosenberg, Z; Yaziv, D.; Yeshurun, Y.; Bless, S.J.
Shear Strength of Shock-Loaded Alumina as Determined with Longitudinal
and Transverse Manganin Gauges.
Journal of Applied Physics, v62 n3, August 1, 1987: 1120-1122.

Rouby, D.; Osmani, H.
Characterization of Interface Debonding in a Ceramic-Ceramic Fibre
Composite Using the Indentation Method and Acoustic Emission.
Journal of Materials Science Letters, November 1988: 1154-1156.

Roylance, David.
Numerical Analysis of Projectile Impact in Woven Textile Structures.
In: An Assessment of Technology for Turbojet Engine Rotor Failures,
edited by Emmett A. Witmer. Cambridge, MA: Massachusetts Institute of
Technology, August 1977: 247-260.

Rugger, George; Fenter, John R.
Ceramic Composite Armor.
In: Kirk-Othmer Encyclopedia of Chemical Technology. n.s., n.d., 2nd
edition: 138-157.

Sakai, Jeffery M.; Grabarek, Chester.
Ballistics Tests on Heat Treated Tungsten Alloy Penetrators After
Swaging.
In: Powder Metallurgy in Defense Technology. Aberdeen Proving Ground,
MD. September 1977. n.s.: Metal Powder Industries Federation, 1977: 85-90.

Sandstrom, Donald J.; Jessen, Nicholas; Loewenstein, Paul; Weirick,
Larry.
Report of the Panel on the Use of Depleted Uranium Alloys for Large
Caliber Long Rod Kinetic Energy Penetrators.
Los Alamos, NM: Los Alamos Scientific Laboratory, n.d.

Scavullo, M.A.; Underwood, J.H.
Laboratory Testing of Long Rod Penetrator and Sabot Components.
n.s., n.d.

Schillalies, Helmut; Storch, Werner; Scholze, Horst.
Determination of the Spalling Resistance of Sintered Alumina Via
Acoustic Emission Analysis. (Bestimmung der Temperaturwechselbestandigkeit
von Sinterkorund mit der Schallemissionsanalyse).
Ceramic Forum International, v58 n1, January/February 1981: 25-30.

Schwer, Leonard E.
Comments on the Paper Entitled: Two- and Three-Dimensional
Computational Approaches for Steel Projectiles Impacting Concrete Targets.
Presented at Post-SMIRT Seminar on Impact. Lausanne, Switzerland.
August 1987. San Jose, CA: APTEK, Inc., October 1987.

Seaman, Lynn; Curran, D.R.; Shockey, D.A.
Scaling of Shear Band Fracture Processes.
In: Material Behavior Under High Stress and Ultrahigh Loading Rates,
edited by John Mescall and Volker Weiss. New York, NY: Plenum Press, n.d.:
295-307.

Semiatin, S.L.; Lahoti, G.D.; Oh, S.I.
The Occurrence of Shear Bands in Metalworking.
In: Material Behavior Under High Stress and Ultrahigh Loading Rates,
edited by John Mescall and Volker Weiss. New York, NY: Plenum Press, n.d.:
119-159.

Seshadri, S.G.; Chia, Kai-Yin.
Tensile Testing of Ceramics.
Communications of the American Ceramic Society, October 1987:
C242-244.

Sharpe, W.N.; Douglas, A.S.
Dynamic Fracture Toughness Testing: Final Report.
Research Triangle Park, NC: Army Research Office, May 15, 1989.

Sharpe, William N.; Douglas, Andrew S.; Shapiro, Jason M.
Dynamic Fracture Toughness Evaluation by Measurement of CTOD.
Baltimore, MD: The Johns Hopkins University, February 1988.

Shockey, D.A.; Caligiuri, R.D.; Eiselstein, L.E.; Marchand, A.H.;
Klopp, R.W.; Florence, A.L.
Technical Support for the Honeywell Blue Team Heavy Armor Program:
Final Report.
Menlo Park, CA: SRI International, December 1988.

Silsby, Graham F.
Penetration of Semi-Infinite Steel Targets By Tungsten Long Rods At
1.3 to 4.5 Kilometers Per Second.
In: Ballistics 8th International Symposium. Orlando, FL. October 23-
25, 1984. Wilmington, MA: Avco Systems Division, 1984: TB.31-TB.36.

Singh, J.P.
A Review of the Effect of Flaws on the Fracture Behavior of Structural
Ceramics.
Argonne, IL: Argonne National Laboratory, September 1986.

Smith, Eleanor R., editor.
Ceramic-Armor Technology: Bibliography.
n.s.: Defense Ceramic Information Center, May 1969.

Smith, Mark T.; Patton, Edward M.
Evaluation of the Deformation Behavior of Nylon Materials Used in
Ballistic Applications.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, June
1986.

Sternberg, Joseph.
Material Properties Determining the Resistance of Ceramics to High
Velocity Penetration.
Journal of Applied Physics, v65 n9, May 1989: 3417-3424.

Sternberg, Joseph.
On the Resistance of Ceramics to High Velocity Penetration.
Monterey, CA: Naval Postgraduate School, July 1988.

Stiglich, Jacob J.
A Survey of Potential Ceramic Armor Materials.
Watertown, MA: Army Materials and Mechanics Research Center, March
1968.

Sturges, J.L.; Cole, B.N.; Bingley, M.S.; Turner, G.I.
The Influence of Strain-Rate and Pressure on the Dynamic Tensile
Behaviour of Depleted Uranium.
n.s., n.d.: 523-530.

Suresh, S.
Constitutive Behavior of Ceramics: Implications for Fracture Under
Cyclic Compressive Loads.
In: Constitutive Modeling for Nontraditional Materials, edited by
V.K. Stokes. New York, NY: American Society of Mechanical Engineers, 1987:
233-247.

Sutcu, M.
Weibull Statistics Applied to Fiber Failure in Ceramic Composites and
Work of Fracture.
Acta Metallurgica, v37 n2, February 1989: 651-661.

Swain, M.V.
Techniques for Evaluating the Fracture Toughness of Ceramics.
In: Australasian Institute of Metals 37th Annual Conference.
Ballarat, Australia. May 13-17, 1985. n.s., 1985: C7-C9.

Szabo, Sue; Dyess, William W.
The New National Armor/Anti-Armor Data Repository.
In: TACOM Armor 4th Coordinating Conference. n.s., 1988: v2, 197-209.

Tardif, H.P.
Metallurgical Activities at CARDE (Canadian Armament Research and
Development Establishment).
Canadian Mining and Metallurgical Bulletin, v49 n529, May 1956:
372-376.

Tate, A.
A Theory for the Deceleration of Long Rods After Impact.
Journal of the Mechanics and Physics of Solids, v15 n6, November
1967: 387-399.

Tate, A.
Further Results in the Theory of Long Rod Penetration.
Journal of the Mechanics and Physics of Solids, v17 n3, June 1969:
141-150.

Tate, A.; Green, K.E.B.; Chamberlain, P.G.; Baker, R.G.
Model Scale Experiments on Long Rod Penetration.
In: Ballistics 4th International Symposium. Monterey, CA. October
17-19, 1978. Arlington, VA: ADPA, 1978: 1-19.

Taylor, L.M.
Implementation of a Vectorized Damage Constitutive Model in the DYNA2D
Finite Element Program.
Albuquerque, NM: Sandia National Laboratories, July 1984.

Taylor, Lee M.; Chen, Er-Ping; Kuszmaul, Joel S.
Microcrack-Induced Damage Accumulation in Brittle Rock Under Dynamic
Loading.
Computer Methods in Applied Mechanics and Engineering, v55 n3, May
1986: 301-320.

Tetelman, A.S.; Evans, A.G.
Failure Prediction in Brittle Materials Using Fracture Mechanics and
Acoustic Emission.
In: Fracture Mechanics of Ceramics Volume 2 Microstructure,
Materials, and Applications, edited by R.C. Bradt. New York, NY: Plenum
Press, n.d.: 895-924.

Tham, R.; Stilp, A.J.
Yield Strength and Flow Stress Measurements of Tungsten Sinter Alloys
At Very High Strain Rates.
Journal de Physique, v49 nC3, September 1988: 85-90.

Tham, Reinhard H.; Stilp, Alois J.
Deformation Mechanisms of Impact-Loaded Tungsten Sinter Materials.
In: Shock Waves and High-Strain-Rate Phenomena in Metals, edited by
Marc A. Meyers. New York, NY: Plenum Press, 1981: 79-89.

Throop, J.F.; Fujczak, R.R.
Fracture Resistant Titanium-Aluminum Laminate.
In: Toughness and Fracture Behavior of Titanium. Philadelphia, PA:
American Society for Testing and Materials, 1979: 246-266.

Tracy, C.; Slavin, M.; Viechnicki, D.
Ceramic Fracture During Ballistic Impact.
In: Advances in Ceramics (Fractography of Glasses and Ceramics), v22,
1988: 295-306.

Ultramet.
Coated Tungsten Powder: Final Report.
Pacoima, CA: Ultramet, April 8, 1987.

Underwood, J.H.; Scavullo, M.A.
Fracture Behavior of a Uranium or Tungsten Alloy Notched Component
With Inertia Loading.
In: Fracture Mechanics 16th National Symposium. Columbus, OH. August
15-17, 1983. Philadelphia, PA: American Society for Testing and Materials,
1983: 554-568.

Vardar, O.; Finnie, I.
The Prediction of Fracture in Brittle Solids Subjected to Very Short
Duration Tensile Stresses.
International Journal of Fracture, v13 n2, April 1977: 115-131.

Viechnicki, D.; Blumenthal, W.; Slavin, M.; Tracy, C.; Skeele, H.
Armor Ceramics--1987.
Presented at TACOM Armor 3rd Coordinating Conference. Monterey, CA.
February 17-19, 1987.

Viechnicki, Dennis J.
Factors Controlling the Ballistic Behavior of Armor Ceramics.
In: Army Science 1986 Conference Proceedings. June 17-19, 1986. n.s.:
Department of the Army, 1986: v4, 233-247.

Watanabe, Tadahiko; Yamamoto, Hideki; Shobu, Kazuhisa; Sakamoto,
Tadashi.
Factors Affecting the Porosity and Bending Strength of Ti(CN)-TiB2
Materials.
Journal of the American Ceramic Society, v71 n4, April 1988:
C202-C204.

Weaver, A.T.
Lightweight Engine Containment.
In: An Assessment of Technology for Turbojet Engine Rotor Failures,
edited by Emmett A. Witmer. Cambridge, MA: Massachusetts Institute of
Technology, August 1977: 235-245.

Wiederhorn, S.M.; Fuller, E.R.
Structural Reliability of Ceramic Materials.
In: Engineering Ceramics 1984 International Symposium. Jerusalem,
Israel. December 16-20, 1984. Israel: Ministry of Science and Development,
1984: 169-186.

Wilcox, B.A.; Gilbert, A.; Allen, B.C.
Intermediate Temperature Ductility and Strength of Tungsten and
Molybdenum TZM.
Wright-Patterson Air Force Base, OH: Air Force Materials Laboratory,
April 1966.

Wilkins, M.L.
Use of Boron Compounds in Lightweight Armor.
In: Boron and Refractory Borides, edited by V.I. Matkovich. Berlin,
Germany: Springer-Verlag, 1977: 633-648.

Wilkins, M.L.; Cline, C.F.; Honodel, C.A.
Fourth Progress Report of Light Armor Program.
Livermore, CA: Lawrence Radiation Laboratory, (June 1969).

Wilkins, M.L.; Landingham, R.L.; Honodel, C.A.
Fifth Progress Report of Light Armor Program.
Livermore, CA: Lawrence Radiation Laboratory, January 1971.

Wilkins, Mark L.
Armor and Long-Rod Penetrator Research (Non-Nuclear Ordnance):
Proposal.
n.s.: Lawrence Livermore Laboratory, July 25, 1978.

Wilkins, Mark L.
Calculation of Elastic-Plastic Flow.
Livermore, CA: Livermore Radiation Laboratory, April 19, 1963.

Wilkins, Mark L.
Mechanics of Penetration and Perforation.
International Journal of Engineering Science, v16 n11, 1978: 793-807.

Wilkins, Mark L.
Penetration Mechanics.
Livermore, CA: Lawrence Radiation Laboratory, November 13, 1969.

Wilkins, Mark L.
Second Progress Report of Light Armor Program.
Livermore, CA: Lawrence Radiation Laboratory, August 11, 1976.

Wilkins, Mark L.; Guinan, Michael W.
Impact of Cylinders on a Rigid Boundary.
Journal of Applied Physics, v44 n3, March 1973: 1200-1206.

Wilkins, Mark L.; Reaugh, John E.
Computer Simulations of Ballistic Experiments.
In: TACOM Armor 3rd Coordinating Conference for Light Combat
Vehicles. n.s., 1987: v2, 231-258.

Wilkins, Mark; Honodel, Charles; Sawle, David.
An Approach to the Study of Light Armor.
Livermore, CA: Lawrence Radiation Laboratory, June 13, 1967.

Wirmer (Wimmer), J.M.; Bransky, I.; Tallan, N.
Impact Resistance of Structural Ceramics: Part 2 Ballistic Tests
(Final Report).
Wright-Patterson Air Force Base, OH: Air Force Materials Laboratory,
February 1976.

Witmer, Emmett A., editor.
An Assessment of Technology for Turbojet Engine Rotor Failures.
Cambridge, MA: Massachusetts Institute of Technology, August 1977.

Wittenauer, J.; Nieh, T.G.
Development of Fine-Grained, Ductile Tungsten Alloys for
Armor/Anti-Armor Applications.
n.s.: Lockheed Missiles and Space Co., Inc., January 31, 1990.

Wood, D.H.; Dini, J.W.; Johnson, H.R.
Tensile Testing of U/5.3 wt% Nb and U/6.8 wt% Nb Alloys.
Journal of Nuclear Materials, v114 n2/3, February 1983: 199-207.

Woodward, R.L.
A Note on the Deformation of Conical Penetrators.
International Journal of Impact Engineering, v2 n4, 1984: 325-330.

Woodward, R.L.; Baldwin, N.J.; Burch, I.; Baxter, B.J.
Effect of Strain Rate on the Flow Stress of Three Liquid Phase
Sintered Tungsten Alloys.
Metallurgical Transactions, v16A n11, November 1985: 2031-2037.

Woodward, R.L.; McDonald, I.G.; Gunner, A.
Comparative Structure and Physical Properties of W-Ni-Fe Alloys
Containing 95 and 25 wt% Tungsten.
Journal of Materials Science Letters, v5 n4, April 1986: 413-414.

Woodward, R.L.; Yellup, J.M.; de Morton, M.E.
Development of a Sintered Tungsten Alloy Penetrator.
Metals Forum, v6 n3, Winter 1983: 175-179.

Woodward, Raymond L.
Penetration of Semi-Infinite Metal Targets by Deforming Projectiles.
International Journal of Mechanical Science, v24 n2, 1982: 73-87.

Woolsey, Patrick; Mariano, Stephen A.; Kokidko, David.
Alternative Test Methodology for Ballistic Performance Ranking of
Armor Ceramics: Final Report.
Adelphi, MD: Army Laboratory Command, April 1989.

Wright, Thomas W.
A Survey of Penetration Mechanics for Long Rods.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, June
1983.

Xavier, Celio; Da Costa, Carlos R.C.
Estudo do Comportamento Mecanico de Placas de Alumina Sob Impacto
Balistico. (A Study of the Mechanical Behavior in Ballistic Impact of Alumina
Plates).
Ceramica, v175 n30, July 1984.

Yaziv, D.; Bless, S.J.; Rosenberg, Z.
Study of Spall and Recompaction of Ceramics Using a Double-Impact
Technique.
Journal of Applied Physics, v58 n9, November 1, 1985: 3415-3418.

Yaziv, D.; Rosenberg, G.; Partom, Y.
Differential Ballistic Efficiency of Applique Armor.
In: Ballistics 9th International Symposium. Shrivenham, UK. April
29-May 1, 1986. n.s., 1986: v2, 2.315-2.319.

Yaziv, D.; Rosenberg, Z.; Shevah, H.
Parametric Study of Ceramic Laminated Armor Configurations
(unclassified pages only).
In: TACOM Armor 3rd Coordinating Conference for Light Combat
Vehicles. n.s., 1987: v2, 366-370, 372, 375.

Yaziv, D; Yeshurun Y.; Partom, Y.; Rosenberg, Z.
Shock Structure and Precursor Decay in Commercial Alumina.
In: Shock Waves in Condensed Matter 1987, edited by S.C. Schmidt.
American Physical Society Topical Conference. Monterey, CA. July 20-23, 1987.
Amsterdam, Netherlands: North-Holland, 1988: 297-300.

Yaziv, Dan.
Shock Fracture and Recompaction of Ceramics: Dissertation.
Ann Arbor, MI: University Microfilms International Dissertation
Information Service, 1989.

Yaziv, Dan; Bless, Stephan.
Shock Wave Compression of Ceramics--A Review.
n.s., June 1983.

Zackay, Victor F.; Parker, Earl R.; Fahr, Dieter; Busch, Raymond.
The Enhancement of Ductility in High-Strength Steels.
Transactions of American Society for Metals, v60, 1967: 252-259.

Zener, C.; Hollomon, J.H.
Effect of Strain Rate Upon Plastic Flow of Steel.
Journal of Applied Physics, v15 n1, January 1944: 22-32.

Zukas, John A.; Collins, John.
A Preliminary Model for Loads on a Penetrator Impacting Concrete.
Aberdeen Proving Ground, MD: Army Ballistic Research Laboratory, June
1981.

APPENDIX B
A REVIEW OF PENETRATION MECHANISMS
AND DYNAMIC PROPERTIES OF TUNGSTEN AND
DEPLETED URANIUM PENETRATORS

A REVIEW OF PENETRATION MECHANISMS AND DYNAMIC PROPERTIES OF TUNGSTEN AND DEPLETED URANIUM PENETRATORS

S. P. Andrew, R. D. Caligiuri, and L. E. Eiselstein

Failure Analysis Associates®, Inc.

149 Commonwealth Drive

Menlo Park, CA 94025

Abstract

Kinetic energy penetrators must possess the best possible combination of hardness, stiffness, strength, and fracture toughness characteristics to be effective against modern armor systems. Over the last decade, depleted uranium (DU) and tungsten alloys have been the materials of choice for kinetic energy penetrators. DU and tungsten perform about the same against semi-infinite targets, and DU outperforms tungsten penetrators in oblique, spaced array targets, but because of environmental and subsequent cost concerns, effort has focused on improving the performance of tungsten penetrators over the last few years. However, despite recent improvements in material properties, the penetration performance of tungsten still lags behind that of DU. One possible reason is the difference in deformation mechanisms at the leading edge of the penetrator during the penetration process—DU alloys tend to shear band and sharpen as they penetrate the target material, whereas tungsten penetrators tend to mushroom and blunt. As a first step to determine whether shear banding is truly the reason for superior DU performance, a review and summary of the available information was performed. This paper presents a review of the fabrication, high strain-rate properties, and penetration phenomena of penetrators manufactured from both tungsten and DU alloys. Specifically, the effects of composition, processing, and heat treatment on material properties and penetration mechanisms of these alloys are discussed.

Introduction

As part of an ongoing effort to develop ballistic/materials correlations useful to the armor/anti-armor research and development community, Failure Analysis Associates, Inc. (FaAA) reviewed, assessed, and compared available information on penetration mechanisms of DU and tungsten penetrator alloys. Variables that influence the performance of kinetic energy penetrators include penetrator material properties and geometry, penetration mechanisms, launch dynamics, velocity, and target material properties and geometry. The objective of this phase of the project was to review, to the extent possible, the effect of material properties and penetration mechanisms on ballistic performance of these two materials. Penetration mechanisms were of particular interest, as it is felt that the differences in these mechanisms may be the reason why DU and tungsten penetrators perform differently. As a first step, FaAA conducted an extensive review of published technical literature, searching the open literature (books, journals, conference proceedings), the DTIC database of unclassified reports, and other government and industry reports. The review and collection process also entailed visits and teleconferences with government and industry personnel.

While numerous recent studies of the differences between penetrator performances have focused on the effects of general penetration mechanics (such as the three penetration phases defined by Wilkins and Reaugh [1]) and on projectile shape differences [2,3,4], the focus of this paper is on the effect of material properties. Data on processing, composition, and heat treatment differences—as reported in studies such as Ekbom et al.'s [5] investigation of swaged and unswaged 93W-4.5Ni-2.5Fe projectiles and Brooks and Erikson's [6] experimental analysis of varying heat treatments and carbon contents of uranium alloys— were compiled as part of the FaAA review. In all, over 100 literature sources were reviewed and over 30 government and industry contacts were made. To the extent that a comprehensive summary of these diverse studies is possible within the scope of this paper, the conclusions of these researchers are presented herein.

Background

When comparing penetrator performance, two types of targets must be considered: 1) monolithic semi-infinite targets in which the line of flight of the penetrator is normal to the target and 2) spaced array targets—oblique targets with multiple plates in which the line of flight of the penetrator is at an angle to the target. DU is currently the most widely used material in the United States for long rod kinetic energy penetrators. Concerns over environmental problems associated with disposal of materials with residual low-level radiation and the perception that DU kinetic energy research is at the mature stage of the development cycle (further improvements in DU's performance are considered to be incremental) have focused more attention on the continued development of alternative penetrator materials—namely tungsten alloys.

Tungsten and Tungsten Alloys - Recent Advances
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141

Despite the concerns about DU alloys, however, they continue to be favored for kinetic energy applications because DU alloys are perceived to outperform tungsten alloys. This perception is due primarily to the superior performance of DU penetrators in oblique impacts. Hence, most of the current research in processing is to improve the performance of tungsten penetrators.

Processing

Research into improving performance through processing is being conducted both at the government laboratory and private industry levels. Some of the processing techniques being used are swaging, texturing, chemical vapor deposition (CVD), and alternative matrix formulations. The potential for use of hydrostatic extrusion and hot rolling processing to fabricate composite DU/tungsten penetrators has also been investigated.

The end goal of most advanced tungsten processing research has been to match the dynamic material properties of DU; this goal was based on the belief that improved material properties would increase the ballistic performance of tungsten. Considerable research has been performed along these lines in recent years, and material properties have been improved. However, improved material properties have not directly correlated with improved tungsten penetration performance. This has been demonstrated in both monolithic semi-infinite and oblique spaced targets; despite the improvement in tungsten properties, the performance of the two materials against monolithic targets is still about the same, and DU still outperforms tungsten against oblique spaced targets. New techniques for forming both tungsten and DU/tungsten composite penetrators show the promise of penetrators that will outperform any of those currently in the United States arsenal, and further development of these penetrators is one objective of current research efforts.

DU's penetration characteristics and availability make it an attractive choice for use as a penetrator material (7). It does, however, pose some processing difficulties. The material is sensitive to corrosion (8), to trace levels of impurities (7), and to variations caused by heat treatment (9). In addition, finely divided DU is pyrophoric; therefore, unlike tungsten alloys, DU alloys cannot be easily processed by powder metallurgy techniques, and, although they can be cast and hot-worked by conventional techniques, they require special machining. Some DU powder metallurgy research is being conducted to see whether rapid solidification processing can be used to advantage; however, little work has currently been published in this area.

DU production usually begins with UF_4 (8, 10), which is derived from a nuclear weapons and power industry byproduct, UF_6. Cast ingots of DU typically retain residual impurities of Fe, Si, Cu, Ni, C, and H_2 from the reduction and vacuum-melt process. Hydrogen embrittlement is a concern for DU alloys, which are also sensitive to re-embrittlement (9, 10). The quality of DU alloys must be carefully controlled to minimize inclusions and mechanical property variations caused by

improper heat treatment. Penrice (9) states that heat treatment after quenching is the single most important step in making quality DU alloy penetrator material. As discussed below, tungsten materials require similar care in processing and heat treatment.

Tungsten Processing

Tungsten alloys used in penetrators are really composite materials. They are composed of hard, brittle tungsten particles embedded in a soft, ductile metal matrix (most often nickel and iron, although copper, cobalt, and other metals have been used for matrix materials to provide ductility to the system). Higher volume fractions of tungsten in the alloy yield heavier penetrators, which in turn have greater kinetic energies for penetration. However, a higher volume fraction of tungsten also yields greater contiguity between tungsten grains (tungsten-tungsten boundaries are fracture initiation sites) and means the alloy must contain less of the ductile matrix which retards cracks and redistributes stresses (11, 12).

Several processes have been used to manufacture tungsten penetrators. Among these are sintering, swaging, extrusion, and CVD processes. Of these, sintering (which is sometimes followed by swaging and annealing to give increased strength and ductility) is the most popular method. Hydrostatic extrusion has also being investigated as a method for making high performance tungsten penetrators. CVD has also been used in some research programs (13), although only to a limited extent and primarily for shaped-charge liner applications.

The sintering process used is liquid-phase and is performed by compacting fine-grained (3-5 micron) tungsten powders and heating them above the eutectic temperature of 1435°C in a hydrogen atmosphere. The resulting composite consists of rounded, tungsten grains (50-90 microns) in a W-Ni-Fe matrix. The tungsten grains retain their BCC structure; however, small amounts of nickel and iron are in solid solution during liquid-phase sintering. Special attention must be paid to ensure complete densification, as small amounts of porosity from entrapped gas or solidification shrinkage will reduce ductility (11,14).

After sintering, the resulting material must be cooled at a rate that will deter the formation of intermetallics that, along with impurities, can weaken the material by facilitating an intergranular rather than transgranular failure mode across the tungsten grains. Although reports of the effects of cooling rates on observed toughness vary, the consensus appears to be that cooling at slow rates allows the formation of intermetallics and allows impurities (i.e., sulfur, carbon, phosphorous) to segregate to the grain boundaries, resulting in lower fracture toughness (11, 14, 15, 16, 17). German et al. (17) note that the effect of cooling rates lessens as the amount of impurities is reduced. It is also important to prevent hydrogen embrittlement from occurring because it, too, weakens the composite and causes intergranular failure to occur (14, 16, 18). As will be discussed in greater detail below, transgranular failures are preferable to intergranular failures, as they allow a material to achieve higher

strength and toughness before failing in quasi-static mechanical tests.

The nickel-iron matrix material has an FCC structure, the ductility of which is dependent on the amount of post-sintering processing. Even though the matrix is ductile, the mechanical behavior of the W-Ni-Fe penetrators approaches that of pure tungsten, since a low volume fraction of matrix material must be used to maximize overall density. This phenomenon can cause tungsten penetrators to break up after initial impact with oblique targets, making them less effective in penetrating subsequent armor plates. Because of this problem, methods have been sought for increasing the ductility at constant overall density. Ductility may be increased by orienting the grains so that they are parallel to one another and parallel to the longitudinal axis of the penetrator. Two methods for accomplishing this are to swage or hot extrude the W-Ni-Fe composite. The resulting preferential grain orientation produces stronger and harder penetrators. Annealing may also be used to increase ductility; it tends to preferentially soften the matrix. The "cold work" in tungsten grains is not significantly affected due to the higher melting temperature of tungsten relative to that of the matrix material.

To find the most appropriate, ductile, matrix material for penetrators, several alloys have been studied extensively (6, 11, 19, 20, 21, 22); primary among these are W-Co, W-Cu-Fe, and various formulations of W-Ni-Fe.

Most of the reported research has focused on the nickel-iron alloy systems. Iron increases the matrix toughness and ductility (23). The W-Ni-Fe system was chosen over the W-Cu-Fe system for several reasons. The metallurgical reasons include that Cu has been noted to segregate to the boundaries and that the contiguity is about 13% higher in the W-Cu-Fe system than in the W-Ni-Fe system (24); also, a greater amount of transgranular cleavage has been observed in W-Ni-Fe alloys. These microstructural differences contribute to the increased performance of the W-Ni-Fe alloys. Furthermore, the ideal ratio of nickel to iron has been determined to be 7:3, as this avoids the formation of intermetallic phases (11). According to Penrice (9), a major factor in the improvement of the W-Ni-Fe alloys over the last decade has been the control of impurities that segregate to the grain boundaries.

Review of Material Properties

While the exact effects of material properties on ballistic performance have not been established, it has become apparent that harder, stronger materials are preferable for impacts into semi-infinite plates and more ductile materials are preferable for oblique impacts into spaced array armors. Improved material properties also have an effect at launch and allow higher launch speeds to be used. Hence, it is necessary to discuss the effects of material properties in order to assess relative penetrator performance.

As discussed below, there are numerous differences in the material properties of DU and tungsten alloys. For example, tungsten alloys work harden faster than DU alloys. DU alloys strain harden at a much slower rate, and still work harden after significant swaging (9). Also, Young's modulus for tungsten alloys is twice as large as for DU (9, 25).

Wood and Dini (26) comment that DU's excellent mechanical properties can be significantly improved by alloying and heat treatment. Wood and Dini note that alloying DU with 2 wt% niobium in the over-aged heat treatment condition significantly increases DU's strength without making its material properties sensitive to variations in heat treatment. Compositions containing greater amounts of niobium (in this case, 5.3 and 6.8 wt%) are more resistant to corrosion and hydrogen embrittlement and can be heat treated in larger sections than is possible for DU-0.75Ti. The higher niobium content, however, reduces the strength-ductility relative to that of DU-0.75Ti. In unrelated research, Magness (27) has suggested that DU alloyed with 6 wt% niobium (DU-6Nb) does not shear band (possibly due to its low strength and high work hardening rate), an observation that, if substantiated, could shed new light on the differences in failure mechanisms between tungsten and DU. Because of the current industry focus on improving tungsten properties, the remainder of this discussion centers on that topic.

Tungsten Material Properties

Material properties are sensitive to impurities, microstructure, and processing variations (11, 18, 28) that make it difficult to establish uniform properties. The material properties that have been recorded to date for tungsten alloys vary widely, and the following discussion makes brief note of these as an aid to those who might want to explore the subjects further.

In general, ductility decreases with increased strain rate, as observed by Kaneko (29) and Penrice (15). Bose et al. (30) confirm this observation for 90W-Ni-Fe; Meyer et al. (31) and Kunze and Meyer (32) find that, for 91% tungsten alloys, ductility decreases as strain rate increases for both the as-sintered and the sintered, swaged, and annealed cases.

Elongations up to 25% (15, 16), 29% (33), and 35% (8) have been reported for tungsten alloys. Ekbom (20) reports that elongation decreases as temperature decreases and that tensile strength increases as temperature decreases. As temperature increases, the strain rate sensitivity of the material decreases (20, 30) and Bose et al. (30) report that both strength and ductility appear to be unaffected by strain rates (up to 40s^{-1}) at 600°C.

The strength of tungsten alloys has been a subject for much research, and the general finding is that, in agreement with most metals, strength increases with increased strain rate (15, 29, 30, 34). Penrice (15) also notes that ductility decreases faster than strength increases for 97W-Ni-Fe systems. Kunze and Meyer (32) confirm that strength also increases with increased strain rate for 91% tungsten alloys; Meyer et al. (31) extend this to both the as-sintered and the sintered, swaged, and

143

annealed conditions, finding the as-sintered condition to be the more strain rate sensitive of the two (by nearly a factor of two).

The effects of swaging were further investigated by Penrice (7), Ekbom (5), and Kunze and Meyer (32). Penrice (7) found that, as for most metals, as swaging and strain rate increase, tensile strength increases and the percent elongation decreases. Annealing after swaging can increase both ultimate tensile strength and elongation.

Kunze and Meyer (32) show yield strength to be greater in compression than tension for tungsten alloys. Woodward (22) tested 90, 95, and 97% W-Ni-Fe alloys in compression from 0.001 1/s to 1000 1/s and reports that flow stress increases with strain rate. Work softening was observed in these alloys when the strain rate was greater than 2 1/s. This phenomenon is attributed to the effect of temperature rise due to plastic deformation.

Work hardening was found by Rabin et al. (14) to increase with increased tungsten content. Johnson (25) found that 90W-7Ni-3Fe alloys work harden as the shear strain rate increases. He also reports that shear strain at failure decreases as shear strain rate increases, and that tungsten alloys show greater strain rate sensitivity than that measured for DU-0.75Ti. Harding (35) found shear stress to increase as the shear strain rate increases, which parallels Abey and Stromberg's findings (36) for pure DU.

Much of the data on fracture toughness of tungsten alloys comes from Kaneko (37), who investigated W-Ni-Fe alloys with a 2:1 nickel-iron ratio. Kaneko found fracture toughness decreases linearly with the increase in the percent of tungsten (91 to 95.5%). This was found to be true for both as-sintered and 30% swaged material, although the as-sintered showed nonlinear behavior. Values at -40°C and 20°C were about the same.

The most effective ratio of tungsten to matrix materials has also been the object of much research. It is generally accepted that the highest strengths are obtained for tungsten contents from approximately 91 to 93%, corresponding to contiguities from 0.3 to 0.4. Rabin et al. (14) recently performed tests for W-Ni-Fe alloys that support the 93% value; current (unpublished) research seems to support the 91% value.

Another subject for research is to establish hardness, tensile strength, and other mechanical properties for the matrix materials in tungsten alloy penetrators. Woodward (12) has done some work on hardness properties. In measuring the hardness of an alloy that had the same composition as the matrix of a 95% tungsten penetrator, he found that the hardness of the matrix was about 27% that of pure tungsten. He also observed that failure of the low density matrix was characteristic of a ductile failure, confirming the intrinsic ductility of the matrix.

Penetration Mechanisms and Ballistic Performance

The literature indicates that, against monolithic steel targets, improved material properties do not guarantee enhanced penetration. In fact, against monolithic steel targets, DU and tungsten alloys perform about the same. Against oblique spaced steel targets, increased ductility/toughness seems to enhance penetration. An advantage of DU penetrators is that they can bend when impacting an oblique target and, hence, face a lower penetration area (38). For this reason, DU alloy penetrators (which are more ductile than tungsten) generally outperform tungsten alloy penetrators against these targets. Processing to increase material properties shows varied results against spaced array targets for tungsten alloy penetrators. Note that most of the available literature records performance against monolithic targets. The spaced-array target data is limited and the performance conclusions presented here are expected to evolve as the programs mature and more data is made available.

Failure Modes Under Dynamic Loading

During penetration, very little of the kinetic energy of long rod penetrators is transferred to the target. Depth of penetration is to a large extent determined by projectile length. Penetration is the process of moving material aside that results when the impact stress is greater than the flow stress of the target. When impact stress exceeds projectile and target flow stress, the projectile material deforms, and target penetration occurs at the expense of projectile erosion (1, 39). Large hydrodynamic stresses created by the confinement of the target material are transmitted to the projectile, and the nearby free surfaces of the projectile are accelerated radially. During this process it is important for the projectile to maintain as sharp a point as possible so that the penetration energy is applied to as small an area as possible. Thus it is better for a penetrator to "sluff off" material that has expanded radially (i.e., through shear failure), rather than for it to deform and take on a "mushroom" shape. The projectile in this impact velocity range is actually decelerated by its own material strength.

The mechanisms by which DU and tungsten projectiles penetrate their targets include hydrodynamic deformation, mushrooming/macroscopic plastic deformation, erosion/localized plastic deformation, brittle fracture, adiabatic shear banding, and melting/thermomechanical interaction. The two penetrator material failure modes of most interest are: 1) mushrooming and 2) shear failure. The mushrooming phenomenon occurs when penetrator material flows radially after its first impact with the target. The shear failure phenomenon occurs when shear stresses separate penetrator material from the rest of the penetrator after it impacts the target. The most applicable difference in these two penetration modes is that the mushrooming failure mechanism expends energy to expand the penetration radially, whereas the more pointed shear failure expends energy to achieve greater penetration. Those penetrators that achieve shear failure at the nose also maintain a greater pressure on the target and make a more effective use of the penetration energy.

It has been noted (6, 40) that, at very high velocities, both DU and tungsten penetrators perform the same against thick, ductile targets. This may be because, at these

velocities, both penetrators have essentially broken up and are flat-ended projectiles. Brooks and Erikson (6) also conclude that DU and tungsten perform about the same at intermediate velocities. They note, however, that at lower speeds, superior mechanical properties do not necessarily mean better performance.

Penetration Mechanisms of DU Alloys

The principal penetration mechanism for DU alloys (DU-0.75Ti and DU-2Mo) against steel targets is adiabatic shear banding (21, 41), with some mushrooming. Adiabatic shear banding was first observed by Zener and Holloman (42) in 1944, and was first noted in penetrators by Tardif in 1956 (43). Shear banding occurs during the high loading that a projectile sees upon impact with a target and allows the material to readily fail along the bands. This action creates the sharpened pencil point and sluffing off of material that allows the projectile to achieve greater penetration.

Adiabatic shear is dependent on the localized generation of heat high enough to soften the material (44). During penetration, the penetrator will deform plastically at high rates of strain. This will result in an increase in the flow stress of the material due to work hardening and a competing decrease in the flow stress due to thermal softening (90-95% of the deformation goes into heat). When thermal softening overcomes the increase in flow stress, adiabatic shearing will occur. Adiabatic shear has also been extensively studied analytically (45, 46, 47), and there is general agreement that susceptibility to adiabatic shear increases as strain hardening decreases and thermal softening increases. This adiabatic shear phenomenon is not particular to any crystal structure, as long as the above thermomechanical requirements are met (21, 39, 48, 49, 50). Other penetration mechanisms have also been proposed for DU into steel targets. For instance, Penrice (9) notes that a low melting temperature Fe-U eutectic can form at the penetrator tip, which helps remove target/penetrator erosion products from the target hole. This is an alternate explanation of the target hole being narrower for the DU penetrators than for the tungsten alloy penetrators. Mach (51) has measured the temperature rise of tungsten alloys penetrating steel targets. He was able to determine that the penetrator temperature, at an impact velocity of 1200 m/s, quickly rises to approximately 1480°C. At impact velocities of 1600 m/s, the temperature rises to approximately 1790°C. Gerlach (52) has documented the formation of Fe-W molten material at the bottom of penetrator holes. Gerlach also states the melting point of the Fe-W is lowered to approximately 1650°C. This evidence of molten material appears to be in agreement with Mach's data.

Because of the properties of DU, the adiabatic shear banding failure mode is noted more often in DU penetrators than in tungsten. However, there have been DU alloys that have been noted not to fail due to adiabatic shear. One such material is DU-6Nb (6, 27). This alloy is thought to be too soft to achieve the thermomechanical instability required for shear banding to occur.

Penetration Mechanisms of Tungsten Alloys

Tungsten projectiles show little evidence of adiabatic shear banding against steel targets. In general, tungsten alloys show little evidence of adiabatic shear banding or brittle fracture of tungsten grains when shot into ceramic composite targets; however, Shockey et al. (53), Rogers (48), and Irwin (21) report the repeated formation of shear bands in the mushroomed ends of tungsten penetrators shot into ceramic and metal targets. Irwin offers the following explanation for this phenomenon. During the mushrooming of a penetrator, a fillet occurs as the penetrator flows radially. This creates high strains in the penetrator material and causes it to shear band and break off. This process repeats itself throughout the penetration process, causing the observed periodic appearance of shear bands.

Against steel targets, the principal penetration mechanism of tungsten alloys is mushrooming, with macroscopic plastic deformation followed by erosion. Ekbom (20) suggests that the deformation of the tungsten composite can be broken into two stages: 1) the deformation of the matrix and 2) deformation of the tungsten. The initial strain is localized mainly in the matrix, which rapidly work hardens so that the tungsten composite, acting as a single unit, deforms according to tungsten deformation behavior.

Recent studies have investigated the penetrator/target interaction. Gerlach (52) studied 92W-5Ni-3Fe penetrators shot against steel targets. Residuals of these targets show evidence that the penetrator melts, leaving plumes of projectile material in the target cavity. Gerlach postulates that target and penetrator materials engaged in the interaction and friction weld zones lose their strengths and are extruded in the direction opposite to the direction of penetration. This may be supported by the ongoing work of Caligiuri and Eiselstein (54), who have discovered, in examination of tungsten penetrators fired against ceramic composite targets, ceramic target material intermingled with the material of the recovered projectile.

Composite Penetrators

In addition to the efforts underway to improve the performance of tungsten penetrators, a significant number of researchers are investigating the possibilities for developing composite DU/tungsten penetrators that would combine DU's ductility with tungsten's strength. In the mid-1970s, Brooks (3) and Norris et al. (38) recognized the importance of strength and ductility to penetrators and suggested that these requirements would probably be best met by some kind of composite penetrator. In particular they suggested mounting a uranium-alloy head onto a tungsten shaft to improve the performance of tungsten penetrators in oblique impact situations. Bruchey and Montiel (55) suggested that the performance of a tungsten core would be enhanced against spaced targets if sheathed with DU.

Bruchey et al. (56) discuss tailoring penetrator properties using metal matrix composite fabrication techniques.

They describe seven different types of penetrators manufactured using metal matrix composite manufacturing techniques. These were then shot against an oblique triple-spaced array. The best penetration was achieved by a coextruded DU/tungsten alloy (best in this case being that which had the highest velocity after penetrating three metal plates). This penetrator exhibited less bending and deviation from line of flight than typical DU-0.75Ti penetrators. The DU/tungsten alloy was fabricated by placing tungsten filaments in DU-0.75Ti ingots and heat treating and extruding the composite. The main advantage of this coextrusion technique was that it was done at low temperature, thus minimizing filament/matrix interaction.

As most of the new composite materials development programs are classified, little mechanical property and penetration data is available. Hence the data presented here is culled from only a few studies and may not be representative of the body of information that currently exists. Principal among the programs that offered information to this study is that being conducted by Los Alamos National Laboratory (LANL) to build composite DU/tungsten penetrators consisting of tungsten rods surrounded by DU (57). LANL indicates that thermomechanical working of the microcomposite material appears to offer the best properties of any composite to date. They are currently evaluating all working technologies to deform the tungsten particles in the DU matrix. To date this program has produced penetrators with a 50% increase in strength over kinetic energy penetrators currently in the US arsenal.

The LANL DU/tungsten rods show a yield strength of 133 ksi and total strain to failure of 56% (compression). Failure occurred in the tungsten rod, not at the DU/tungsten interface. Ultimate strength was measured to be approximately 75 ksi with very little ductility. Initial tests shot these penetrators into semi-infinite RHA, and they performed as well as the DU-0.75Ti penetrators.

LANL will continue to investigate technologies that will produce aligned tungsten fibers in the uranium matrix. They have demonstrated the ability to deform tungsten particles using swaging, rolling, or hydrostatic high energy rate forming. To date thermomechanical working of the material has been by rolling. The current approach is to work the tungsten and uranium matrix under two separate conditions to optimize material properties in each material. Since uranium recrystallizes at a lower temperature than tungsten, the uranium matrix is worked and annealed repeatedly without recrystallizing the tungsten. They estimate that very large warm working reductions will be required to adequately deform tungsten particles.

Conclusions

The ballistic performance of DU and tungsten alloys against ceramic composite targets cannot be reliably concluded from available literature, although data may be available from classified sources. The dramatic variation in the performance of the two materials against monolithic steel and oblique spaced steel targets, and the

significant effect that an increase in ductility/toughness can have on the ballistic performance of both materials against spaced arrays indicates that a comprehensive effort should be undertaken to correlate material properties with penetrator performance.

One possible reason for the difference in penetration for the two materials is that DU is more ductile than tungsten and less likely to fracture upon impact. DU also has a greater resistance to bending moments resulting from penetration of spaced arrays. Furthermore, the essentially equivalent penetration performance between DU and tungsten in semi-infinite targets suggests that the facts that DU is more susceptible to adiabatic shearing and that tungsten tends to mushroom have only a secondary effect on penetration.

Conclusions, based on available data, include:

- DU alloys and tungsten alloys respond differently to high-rate loading conditions, both in terms of mechanical properties and failure (penetration) mechanisms.

  - Under tensile loading, DU alloys exhibit a higher ultimate tensile strength and a higher strain to failure than tungsten alloys.

  - Under shear loading, DU alloys and tungsten alloys exhibit similar strengths, but DU alloys exhibit a higher strain to failure.

  - Against steel targets, both DU and tungsten tungsten penetrator tips undergo ductile flow. However, subsequent penetration results in bulged tip sharpening by shearing (adiabatic or not). This sharpening occurs more readily in DU than tungsten.

  - Against ceramic composite targets, tungsten alloys penetrate by erosion/localized plastic deformation.

- The ballistic performance of DU alloys and tungsten alloys against monolithic steel targets is similar — at best a 5 to 10% difference. Current improvements in mechanical properties of DU alloys and tungsten alloys give at best a 5 to 10% improvement in ballistic performance.

- Against oblique spaced arrays, DU alloys outperform tungsten alloys. A significant increase in ductility/toughness could result in a substantial improvement in ballistic performance of tungsten penetrators.

It appears that the best way (in the short-term) to improve the ballistic performance of tungsten alloy penetrators against oblique spaced arrays is to improve their resistance to fracture during penetration. It may be ultimately possible to achieve a sharper tip during penetration in tungsten alloys, similar to that which occurs in DU, by proper microstructural control.

References

1. M. L. Wilkins and J. E. Reaugh, "Computer Simulations of Ballistic Experiments," 3rd Tacom Armor Coordinating Conference For Light Combat Vehicles, Vol. II, 1987, pp. 231–258.

2. R. L. Woodward, "A Note on the Deformation of Conical Penetrators," International Journal of Impact Engineering, Vol. 2, No. 4, 1984, pp. 325–330.

3. P. N. Brooks, "Ballistic Impact—The Dependence of the Hydrodynamic Transition Velocity on Projectile Tip Geometry," DREV Report 4001/74, Defence Research Establishment: Valcartier, Quebec, 1974.

4. J. A. Zukas, T. Nicholas, H. F. Swift, L. B. Greszczuk, and D. R. Curran, Impact Dynamics, John Wiley & Sons: New York, 1982, pp.204-209.

5. L. Ekbom, S. Bogegard, L. Holmberg, and L. Westerling, "A Comparison of the Mechanical Properties of KE Penetrator Tungsten Alloys and Their Ballistic Performance," Proceedings of the 9th International Symposium on Ballistics, Royal Military College of Science: Shrivenham, 1986.

6. P. N. Brooks and W. H. Erickson, "Ballistic Evaluation of Materials for Armour Penetrators," DREV Report 643/71, Defence Research Establishment: Valcartier, Quebec, 1971.

7. T. W. Penrice, "Refractory Metals in Ordnance," Proceedings of the 1983 Annual Powder Metallurgy Conference, ed. S. Nayar, S. Kaufman, and K. Meiners: New Orleans, Louisiana, 1983, pp. 507–513.

8. P. K. Johnson, "Tungsten versus Depleted Uranium for Armour-Piercing Penetrators," Refractory and Hard Metals, 1983, pp. 179–182.

9. T. W. Penrice, "Tungsten and Depleted Uranium for Kinetic Energy Penetrators," Proceedings of Fourth International Tungsten Symposium, Vancouver, British Columbia, 1987, pp. 140–151.

10. D. J. Sandstrom, N. Jessen, P. Loewenstein, and L. Weirick, "Report of the Panel on the Use of Depleted Uranium Alloys for Large Caliber Long Rod Kinetic Energy Penetrators," 2nd Charlottesville Conference on High Density Penetrator Materials, Foreign Science Technology Center: Charlottesville, Virginia, 1980, pp. 2–7.

11. R. M. German, "Microstructure Limitations of High Tungsten Content Heavy Alloys," Eleventh International Plansee Seminar '85: New Applications, Recycling and Technology of Refractory Metals and Hard Materials, ed. H. Bildstein and H. M. Ortner: Reutte, Austria, 1985.

12. R. L. Woodward, I. G. McDonald, and A. Gunner, "Comparative Structure and Physical Properties of W-Ni-Fe Alloys Containing 95 and 25 Wt.% Tungsten," Journal of Material Science Letters, Vol. 5, No. 4, pp. 413–14.

13. J. Whittenhauer and T. G. Nieh, "Development of Fine-Grained, Ductile Tungsten Alloys for Armor/ Anti-Armor Applications," Lockheed Missiles & Space Company, Inc., Report No. LMSC-F382002, 1990.

14. B. H. Rabin, A. Bose, and R. M. German, "Characteristics of Liquid Phase Sintered Tungsten Heavy Alloys," The International Journal of Powder Metallurgy, Vol. 25, No. 1, 1989, pp. 21–27.

15. T. W. Penrice, "Developments in Materials For Use as Kinetic Energy Penetrators," Powder Metallurgy in Defense Technology, Vol. 5, 1980, pp. 11–21.

16. L. Ekbom, "The Influence of Microstructure of Liquid-Sintered Tungsten-Base Composites on the Mechanical Properties," Scandinavian Journal of Metallurgy, Vol. 5, No. 4, pp. 1976, 179–184.

17. R. M. German, J. E. Hanafee, and S. L. DiGallonardo, "Toughness Variation with Test Temperature and Cooling Rate for Liquid Phase Sintered W-3.5Ni-1.5Fe," Metallurgical Transactions A, Volume 15A, 1984, pp. 121–128.

18. M. R. Eisenmann and R. M. German, "Factors Influencing Ductility and Fracture Strength in Tungsten Heavy Alloys," International Journal of Refractory and Hard Metals, Vol 3, No. 2, 1984, pp. 86–91.

19. R. Tham, A. J. Stilp, "Yield Strength and Flow Stress Measurements of Tungsten Sinter Alloys at Very High Strain Rates," Journal De Physique, Colloque C3, Supplement au n. 9, Tome 49, 1988.

20. L. Ekbom, "Microstructural Study of the Deformation and Fracture Behavior of a Sintered Tungsten-Base Composite," Modern Developments in Powder Metallurgy, Vol. 14, 1980, pp.177–188.

21. G. J. Irwin, "Metallographic Interpretation of Impacted Ogive Penetrators," DREV Report R-652/72, Defence Research Establishment: Valcartier, Quebec, 1972.

22. R. L. Woodward, N. J. Baldwin, I. Burch, and B. J. Baxter, "Effect of Strain Rate on the Flow Stress of Three Liquid Phase Sintered Tungsten Alloys," Metallurgical Transactions A, Vol. 16A, 1985, pp. 2031–2037.

23. S. Goddard, "Selection of a Kinetic-Energy Threat For Light-Armor Developers" 3rd Tacom Armor Coordinating Conference For Light Combat Vehicles, 1987, pp. 169–189.

24. C. Lea, B. C. Muddle, and D. V. Edmonds, "Segregation to Interphase Boundaries in Liquid-Phase Sintered Tungsten Alloys," Metallurgical Transactions A, Vol. 14A, 1983, pp. 667–677.

25. G. R. Johnson, J. M. Hoegfeldt, U. S. Lindholm, and A. Nagy, "Response of Various Metals to Large Torsional Strains Over a Large Range of Strain Rates-Part 2: Less Ductile Metals," Transactions of the ASME, Vol. 105, 1983, pp. 48–53.

26. D. H. Wood and J. W. Dini, "Tensile Testing of U/5.3 wt% Nb and U/6.8 wt% Nb Alloys," Journal of Nuclear Materials, Vol. 114, 1983, pp. 199–207.

27. L. Magness, Ballistics Research Laboratory, personal communication, 1990.

28. A. C. Chilton and A. S. Wronski, "The Effects of Strain Rate and Pressurization on the Ductile-Brittle Transition Temperature of Polycrystalline Sintered Tungsten," Journal of Less Common Metals, Vol. 17, No. 4, 1969, pp. 447–450.

29. T. Kaneko, "Effect of Heat-Treatment on Dynamic Mechanical Properties of W-Ni-Fe Heavy Alloys," Journal of the Japan Society of Powder and Powder Metallurgy, Vol. 36, No. 1, 1989, pp. 43–48.

30. A. Bose, D. Sims, and R. M. German, "Test Temperature and Strain Rate Effects on the Properties of a Tungsten Heavy Alloy," Metallurgical Transactions A, Vol. 19A, 1988, pp. 487–494.

31. L. W. Meyer, H. D. Kunze, and E. Staskewitsch, "Dynamic Strength and Ductility of a Tungsten-Alloy For KE-Penetrators in Swaged and Unswaged Condition Under Various Loadings," Seventh International Symposium on Ballistics Proceedings, The Hague, Netherlands, 1983, pp. 289–293.

32. H. D. Kunze and L. W. Meyer, "Materials For Extreme Dynamic Loads," Metallurgical Applications of Shock-Wave and High-Strain-Rate Phenomena, Marcel Dekker, Inc., 1986.

33. R. H. Krock and L. A. Shepard, "Mechanical Behavior of the Two-Phase Composite, Tungsten-Nickel-Iron," Transactions of the Metallurgical Society of AIME, Vol. 227, 1963, pp. 1127–1134.

34. T. Nicholas, "Dynamic Tensile Testing of Structural Materials Using a Split Hopkinson Bar Apparatus," Technical Report AFWAL-TR-80-4053, Materials Laboratory, Air Force Wright Aeronautical Laboratories, 1980.

35. J. Harding and J. Huddart, "The Use of the Double Notch Shear Test in Determining the Mechanical Properties of Uranium at Very High Rates of Strain," Proceedings of the Second Conference on Mechanical Properties of Materials at High Rates of Strain, Conference Series Number 47, Institute of Physics: Oxford, England, 1979.

36. A. E. Abey and H. D. Stromberg, "Shear Strength of Beryllium, Uranium, and Tungsten as a Function of Strain, Strain Rate, and Pressure," Journal of Basic Engineering, ASME Transactions, Vol. 93, Series D, No. 2, 1971, pp. 291–295.

37. T. Kaneko, "Fracture Toughness of W-Ni-Fe Heavy Alloys," Journal of the Japan Society of Powder and Powder Metallurgy, Vol. 35, No. 8, 1988, pp. 757–762.

38. D. M. Norris, J. K. Scudder, W. H. McMaster, and M. L. Wilkins, "Mechanics of Long-Rod Penetration at High Angles of Obliquity," UCRL-77941, Conference on High Density Alloy Penetrator Materials, Army Materials and Mechanics Research Center, 1976.

39. M. Wilkins, "Mechanics of Penetration and Perforation," International Journal of Engineering Science, Vol. 16, 1978, pp. 793–807.

40. C. Cline, Lawrence Livermore National Laboratory, private communication, 1990.

41. D. C. Erlich, L. Seaman, T. Cooper, R. D. Caliguiri, and D. R. Curran, "Computational Model for Armor Penetration," SRI Project PYU 7893, SRI International: Menlo Park, California, 1983.

42. C. Zener and J. H. Holloman, "Effect of Strain Rate Upon Plastic Flow of Steel," Journal of Applied Physics, Vol. 15, No. 1, 1944, p. 32.

43. H. P. Tardif, "Metallurgical Activities at CARDE," The Canadian Mining and Metallurgical Bulletin, May 1956.

44. J. H. Giovanola, "Adiabatic Shear Banding Under Pure Shear Loading. Part II: Fractographic and Metallographic Observations," Mechanics of Materials, Vol. 7, 1988, pp. 73–87.

45. R. F. Recht, "Catastrophic Thermoplastic Shear," Transactions of the ASME Journal of Applied Mechanics, Vol. 31, Series E, No. 2, 1964, pp. 189–193.

46. S. L. Semiatin, G. D. Lahoti, and S. I. Oh, "The Occurrence of Shear Bands in Metalworking," Material Behavior Under High Stress and Ultrahigh Loading Rates, Conference at Lake Placid, New York, 1982, pp. 119–159.

47. G. B. Olson, J. F. Mescall, and M. Azrin, "Adiabatic Deformation and Strain Localization," Shock Waves and High Strain Rate Phenomena, ed. M. A. Meyers and L. E. Man, Plenum Press: New York, 1981.

48. Rogers, H. C., "Adiabatic Plastic Deformation," Annual Review of Materials Science, 1979, pp. 283-311.

49. H. C. Rogers, "Adiabatic Shearing—General Nature and Material Aspects," Material Behavior Under High Stress and Ultrahigh Loading Rates, Conference at Lake Placid, New York, 1982, pp. 101–118.

50. L. Seaman, D. R. Curran, and D. A. Shockey, "Scaling of Shear Band Fracture Processes," Material Behavior Under High Stress and Ultrahigh Loading Rates, ed. J. Mescall and V. Weiss, Plenum Press: New York, 1982, pp. 295–307.

51. H. Mach, "Surface Temperature of Rod-Shaped Projectiles after Penetrating an Armor Plate," Report no: BMVG-FBWT-75-7, Institut Franco-Allemand de Recherches: St. Louis, France, 1975.

52. U. Gerlach, "Microstructural Analysis of Residual Projectiles—A New Method to Explain Penetration Mechanisms," Metallurgical Transactions A, Vol. 17A, No. 3, 1986, pp. 435–442.

53. D. A. Shockey, A. H. Marchand, S. R. Skaggs, G. E. Cort, M. W. Burkett, and R. Parker, "Failure Phenomenology of Confined Ceramic Targets and Impacting Rods," Journal of Impact Engineering, (to be published).

54. R. D. Caligiuri and L. E. Eiselstein, Failure Analysis Associates, Inc., unpublished work in progress from Phase II Blue Armor Program, 1990.

55. W. J. Bruchey, Jr. and D. M. Montiel, "Mechanical Property Evaluation of a Series of Commercial Tungsten Alloys," Memorandum Report BRL-MR-3606, AD-A-185-440, U.S. Army Ballistic Research Laboratory: Aberdeen Proving Ground, Maryland, 1987.

56. W. J. Bruchey, A. J. Ricchiazzi, and E. T. Roecker, "Fibre-Reinforced Materials for High Density Penetrators," Sixth International Symposium on Ballistics, Orlando, Florida, 1981, pp. 340–348.

57. P. Dunn and B. Damkroger, Los Alamos National Laboratory, personal communication, 1990.